ARCTIC PERMAFROST ATLAS

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Contents

Foreword

The word "atlas" was coined by the renowned Flemish geographer and cartographer, Gerardus Mercator. In 1595, he published a series of maps intertwined with text and epitaphs, much like a modern-day atlas. Seeing this comprehensive effort as more than just a collection of maps, he aptly named his work *Atlas, or Cosmographical Meditations Upon the Creation of the Universe*. Our endeavour in this Arctic Permafrost Atlas is not so grandiose, but it directly stems from the vision of Mercator to use maps and text to empower the reader through a holistic view of the Earth.

Maps are powerful instruments for conveying timely information to society in a visually pleasing way. Where words might fall short, maps provide an added layer of understanding. On the other hand, words and stories can provide a depth and emotional context that maps may be unable to represent. In this atlas, we tried to deliver maps and graphics of the highest quality mixed with text, art, and stories to explain some of the complex processes associated with permafrost. We aimed to evoke the experiences of people living on and researching permafrost. The 82 maps and graphics, more than 50,000 words and nine stories cannot entirely do justice to the richness and complexity of the "country of permafrost", a term coined by Edward A.G. Schuur and colleagues in 2022, but together they form an unprecedented effort to capture the essence of permafrost characteristics and the issues at stake for local, regional, and global policy in a single document. It was made possible through the involvement of researchers and consortium partners, as well as the results from the European Union Horizon 2020 project NUNATARYUK (2017–2023).

Indeed, this atlas comes at a time when the word "permafrost" has morphed from a relatively unknown academic subject into a topic referenced across news outlets and discussed by the global public. People are aware of it or have heard about it somewhere. Over the past 20 years, the number of web searches for the term "permafrost" has nearly doubled in proportion to the total amount of searches. Part of this growing interest comes from permafrost's relevance to global climate policy and local community adaptation. Climate scenarios show that thawing permafrost will emit between 50 billion and 200 billion tons of carbon dioxide equivalents by the end of the century. Adaptation costs for communities built on permafrost could skyrocket to USD 182 billion by mid-century. The European Union made permafrost one of its eight focal areas in its Arctic policy published in 2021, highlighting the urgency of tackling the issue from both research and policy perspectives.

This atlas is an attempt to translate and consolidate the available knowledge on permafrost. It is a timely book suffused with the compelling enthusiasm of its authors and contributors. Close to a hundred individuals participated in its making, and it does a magnificent job at describing permafrost with maps, words, art, and stories. Far from being an academic product in the traditional sense, it gathers knowledge from the voices of scientists, Indigenous Peoples, northern residents, and local practitioners to provide a holistic and inclusive view of today's challenges in the "country of permafrost".

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Prologue

The cryosphere is the part of the Earth that is frozen at any time. Snow, ice, glaciers, ice sheets, and ice caps are all part of the cryosphere –and so is permafrost. All the components of the cryosphere contribute to and are evidence of the Earth's cooling system. A sensitive sentinel, the cryosphere reacts to fluctuations in temperature. However, as humans warm the Earth at an unprecedented rate, this cooling system can no longer cope and is shrinking.

The changes in snow and ice across land, glaciers, ice caps, and sea ice have long been evident because they are readily observable and measurable. Reflective sea ice in the Arctic Ocean is being replaced by open waters, while melting ice bodies on land – the Earth's "water towers" – are accelerating global sea level rise. The effects on permafrost, however, are less conspicuous and have received less attention beyond the scientific community and Arctic residents. Nevertheless, permafrost is undergoing rapid changes with implications for the entire planet.

Lying beneath the surface of the land and the ocean, permafrost is seldom visible to us. Yet it is comparable in size to other components of the cryosphere, rivalling Antarctica in spatial extent. Like other parts of the cryosphere, permafrost is absorbing heat. The overall volume of ice melting from permafrost today is similar to the amount of ice annually lost in Antarctica: about 150 billion tonnes of water each year. This is enough water to increase sea level by approximately 0.4 millimetres. The extent to which this water reaches the ocean is uncertain, but the melting ice within permafrost means that the land surface in many ice-rich permafrost regions is "falling" much faster than the sea is rising, creating challenges for communities across the Arctic and along the Arctic coast. What truly distinguishes permafrost from its cryosphere counterparts is not so much its water content but the amount of carbon it contains. The frozen remains of plants and animals in permafrost have long made it a significant carbon sink for hundreds of thousands, or even millions, of years. It is our global freezer! But as permafrost thaws, this organic material begins to decompose, resulting in the production and release of greenhouse gases. Given the size of the permafrost system and the vast quantity of organic carbon it contains, the implications for global warming are serious.

The latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) clearly states the importance of permafrost for the Earth's climate. As permafrost thaw expands with global warming, both its area and volume continue to decrease, leading to broad and irreversible changes in Arctic ecosystems that threaten not only flora and fauna but also the lives, livelihoods, and cultural identities of Arctic peoples. The report also emphasises that the ongoing release of greenhouse gases from permafrost thaw will feed back into climate change, aggravating warming now and for centuries to come, thus increasing the challenges we face as a society – a global society.

What is certain is that over the past 50 years, change has been accelerating in the Arctic. The Arctic has warmed nearly four times faster than the global average because of a combination of climate feedbacks, a process known as Arctic amplification. Over the same period, permafrost has warmed by 2 to 3 °C. If global warming continues, the Arctic will experience further warming and permafrost thawing.

As more attention is directed towards understanding the role of permafrost in the climate system and the various aspects of loss and damage associated with permafrost thaw, an ever-growing body of literature has emerged from both the natural and social sciences. The primary goal of the Arctic Permafrost Atlas is to consolidate these recent findings and offer insights into the diverse aspects and impacts of permafrost and permafrost thaw. In doing so, it aims to provide greater insight into the role and impacts of permafrost thaw, share knowledge to help mitigate uncertainties, and facilitate adaptation to changing conditions, especially with respect to infrastructure, food security, and mobility. It endeavours to be both informative and motivating, contributing to a deeper understanding of this largely invisible yet vitally important component of the Earth's ecosystem.

The Arctic Permafrost Atlas also strives to assess the impacts of permafrost change on Indigenous Peoples of the Arctic. While people across the Arctic may have adopted a more modern lifestyle, Indigenous Peoples continue to maintain close ties to the land as a means of preserving their culture, knowledge, and traditional food supply. However, the dramatic impacts of permafrost thaw on Arctic ecosystems now place thousands of years of cultural tradition at risk.

Finally, there is no single definition of the Arctic. Across this vast area, there are great social, cultural, physical, ecological, and economic differences. Permafrost change itself is highly diverse and specific to each location. In this atlas, the many dimensions of permafrost change are addressed across the northern hemisphere without adhering to a strict definition of the Arctic or associating it solely with the occurrence of permafrost, for, as the climate warms and permafrost thaws, the Arctic as we currently see it will also diminish.

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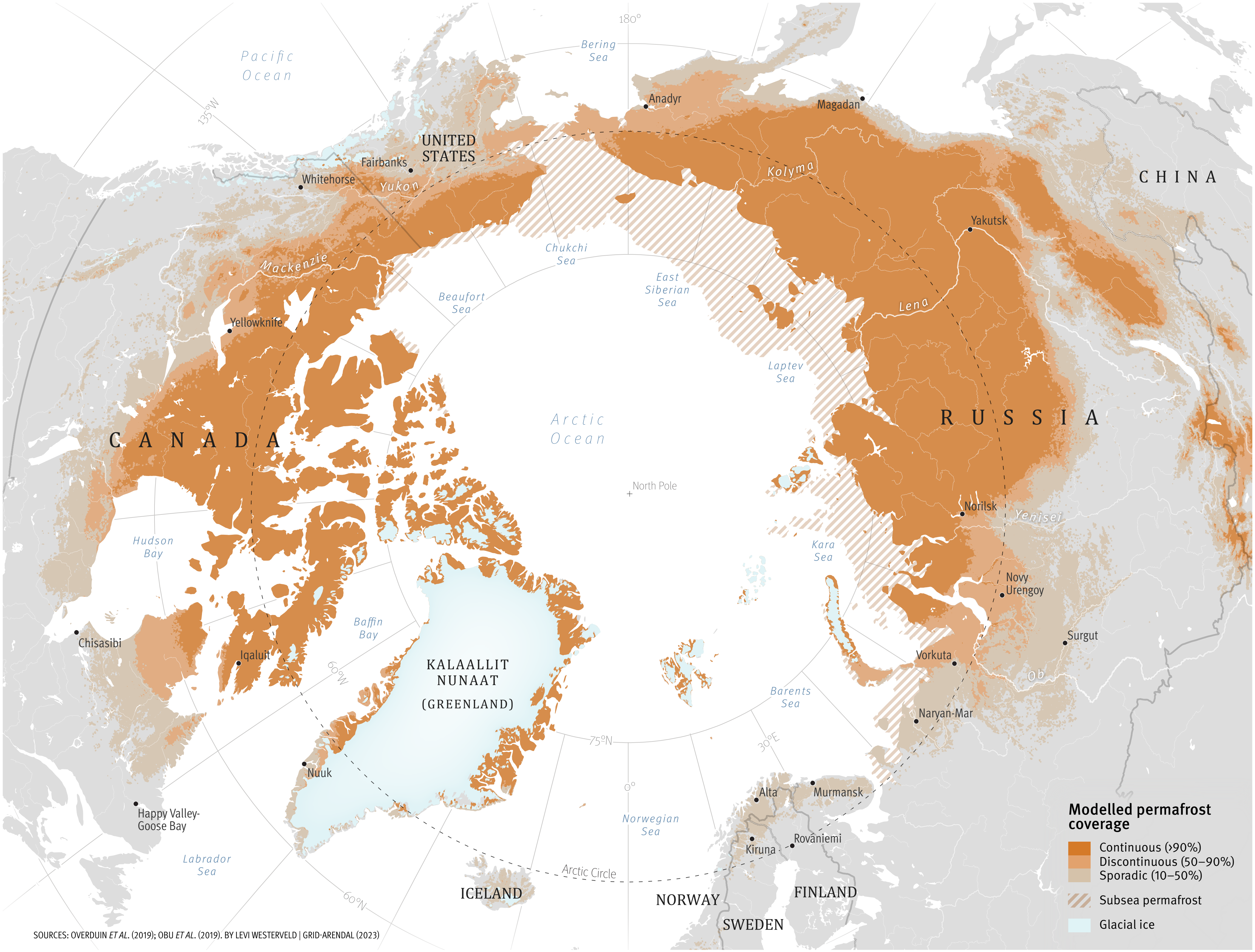
Earth's Freezer

Introduction to Permafrost



SOURCES: OVERDUIN *ET AL.* (2019); OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Frozen grounds

Permafrost in the Arctic

Permafrost, ground that remains frozen for at least two years, occurs in Earth's coldest reaches: the Arctic and boreal zones, Antarctica, and high-altitude regions. This vast but largely unseen landscape characteristic influences not only the flora and fauna of these regions, but also the lives, livelihoods, and cultures of the people who live and work there.

The phenomenon of "permanently" frozen ground was known in Medieval Russia but was only scientifically described in 1757 by the Russian scientist Mikhael Lomonosov. The first maps delineating the extent of the so-called "permanent frost" began appearing in the late 1880s for Siberia and then for the entire Arctic in 1928. The term "permanent frost" was eventually replaced by "perennially-frozen ground". Now, the accepted definition for permafrost is: "ground (soil or rock and included ice and organic material) that remains at or below 0 °C for at least two consecutive years".

Globally, permafrost underlies between 14 and 16 million square kilometres of the Earth's exposed land surface, roughly the area of Antarctica. Most of the world's permafrost is found in the northern hemisphere where it underlies about 15 per cent of the exposed land area. It is found virtually everywhere in the Arctic. The largest expanses of permafrost occur in Alaska, Canada, Kalaallit Nunaat (Greenland), Russia, and on the Tibetan Plateau. Smaller areas of permafrost occur in Iceland, Scandinavia, Svalbard, and in high mountain areas of Europe. In the southern hemisphere, permafrost is found in the Andes and Antarctica. For permafrost on land, scientists distinguish four different permafrost zones based on the proportion of the ground that is permanently frozen: continuous, discontinuous, sporadic, and isolated.

In the **continuous zone**, 90 per cent or more of the landscape is underlain by permafrost. It extends under most surfaces, except for rivers and deep waterbodies, and may reach hundreds of metres deep.

In the **discontinuous zone**, permafrost underlies 50–90 per cent of the landscape. As the name suggests, this zone is broken into areas with and without permafrost, where permafrost does not exist under south-facing slopes. The transition from continuous to discontinuous permafrost generally follows the transition from tundra to subarctic boreal vegetation, although there is no sharp boundary between the two zones. In the discontinuous permafrost zone, the mean annual ground temperature usually measures above −2 °C. Permafrost thickness has a much greater range in the discontinuous zone, varying from a few metres to several hundred metres.

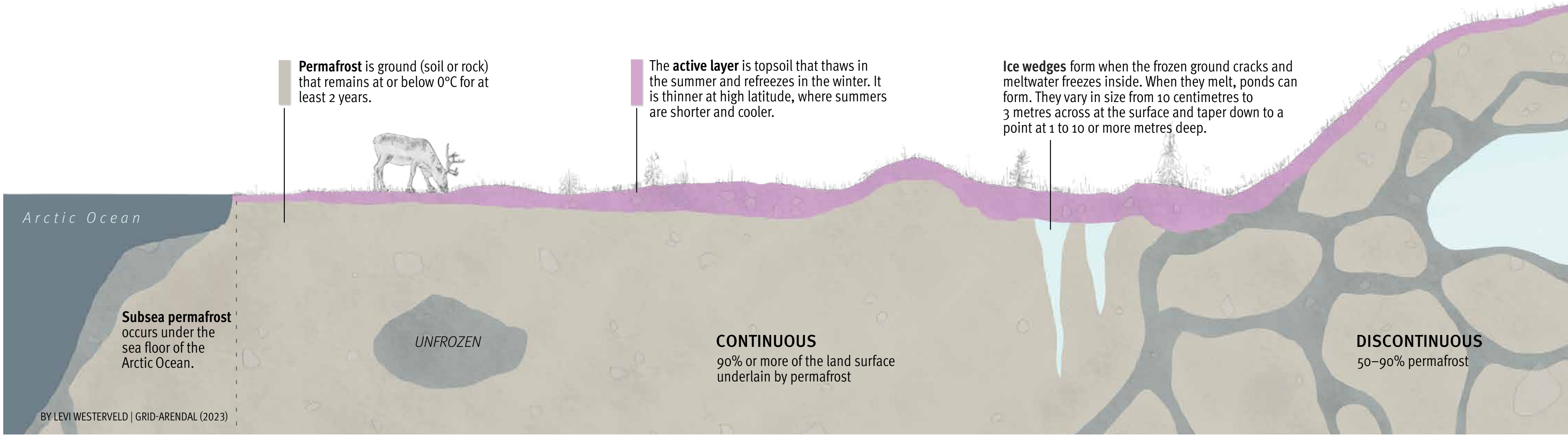
Near the southern extent of the discontinuous zone, permafrost occurs in the **sporadic and isolated patches zones**, underlying 10–50 per cent and less than 10 per cent of the landscape, respectively. This permafrost is patchy in its distribution, tending to occur under north-facing slopes and in peatlands, where permafrost-free areas are common. The thickness of the permafrost ranges from a few metres to over one hundred metres. Permafrost in Finland, Sweden, and mainland Norway largely occurs as discontinuous or sporadic permafrost.

Permafrost also exists in vast areas below the seabed. **Subsea permafrost** occurs in the Arctic continental shelves in a large swath extending offshore of the Russian coast from the Barents Sea to the Chukchi Sea and beyond to the Alaskan and north-western Canadian continental shelves. The extent of this subsea permafrost is estimated to be 2.5 million square kilometres. The greatest areas, more than 60 per cent of this type of permafrost, are found in the Kara, Laptev, East Siberian, and Chukchi Seas. In these seas, the mean thickness of permafrost can reach over 400 metres below the sea floor.

Permafrost in profile
Landscape features

There are numerous unique landscape features and geomorphological processes associated with permafrost environments. The ground above permafrost that is subject to annual freezing and thawing is called the **active layer**. The active layer plays an important role in Arctic ecosystems as this is where most hydrological, biogeochemical, and soil processes occur. The thickness of the active layer primarily depends on the summer heating of the ground as well as the properties of the soil. In general, thicker or deeper active layers occur in areas with warmer summers, although local conditions such as vegetation, duration, thickness of snow cover, and soil moisture also have an influence. In the High Arctic, where summers are cool and short, the active layer may only be a few centimetres thick. Where summers are warmer, the depth of the active layer may reach a metre or more. In peat-rich landscapes, the active layer may be very thin because the peat insulates the permafrost in summer. The change in active layer thickness is one of the features of climate warming in the Arctic and is thus a focus of scientific monitoring.

Ice wedges are common in permafrost landscapes, mainly seen as polygonal networks on the landscape surface. The ice wedges vary in size from a few centimetres to 3 metres across at the surface and taper down to a point 1–10 metres or more deep. Ice wedges form when vertical cracks open in the ground during rapid winter cooling (causing soil contraction) and subsequently fill with spring meltwater. As the water refreezes, it creates a vertical ice vein in the ground and serves as a natural zone of weakness for repeated cracking in successive winters. Because only the active layer on top of the permafrost thaws, the wedge shape is maintained over the summer. As the process can repeat each year, the ice wedge widens over time, pushing the soil around the wedge to create ridges. When the soil material contracts during rapid freezing, the stress is ultimately relieved by the formation of frost cracks that intersect each other in a polygonal shape creating ice-wedge polygons. The polygons can range in size from a few to 50 metres across, may host a pond, and are most common in the continuous permafrost zone. They play a role in controlling microclimate, water movement, and greenhouse gas flux from permafrost. When ice wedges melt, they can form networks of trenches or gullies with mounds of the remaining sediment up to several metres high in between. These mounds are home to several species of animals because they provide a unique habitat that is warmer and drier than the surrounding area.



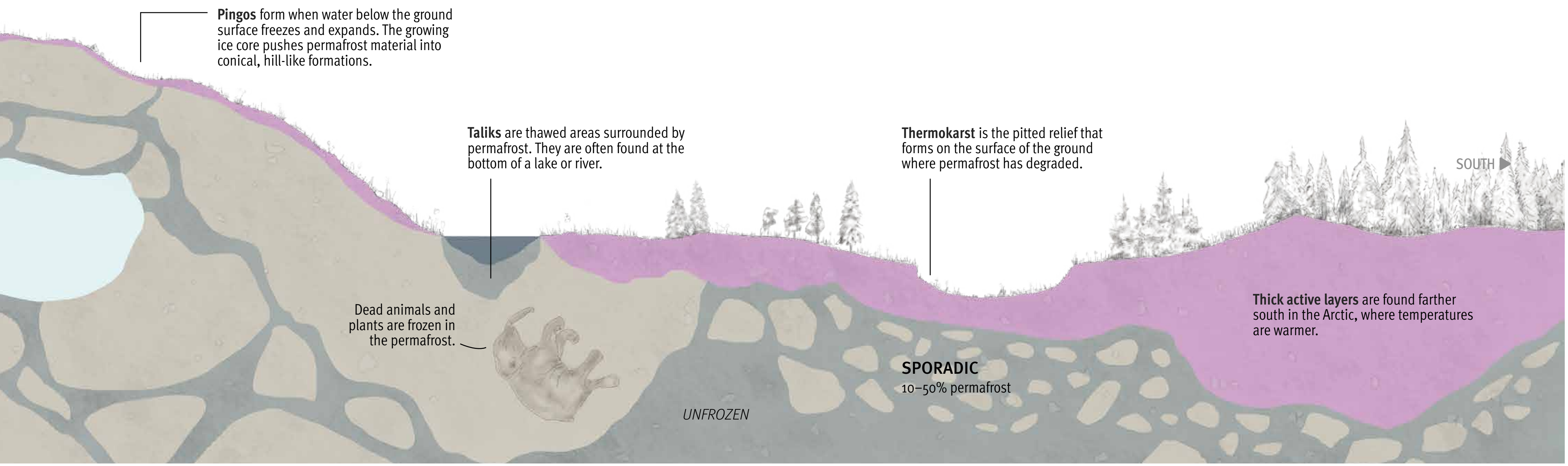
Pingos are large conical hills comprising a massive ice core covered with soil and vegetation. They form where water is injected into the permafrost or when a talik refreezes beneath a former lake, leading to growth of an ice core which pushes up the overlying soil. Occurring in both the continuous and discontinuous permafrost zones, pingos range in size from three to more than 50 metres in height and can reach 1,000 metres in diameter. They have either a circular or oval base and a fissured top that may also contain a crater.

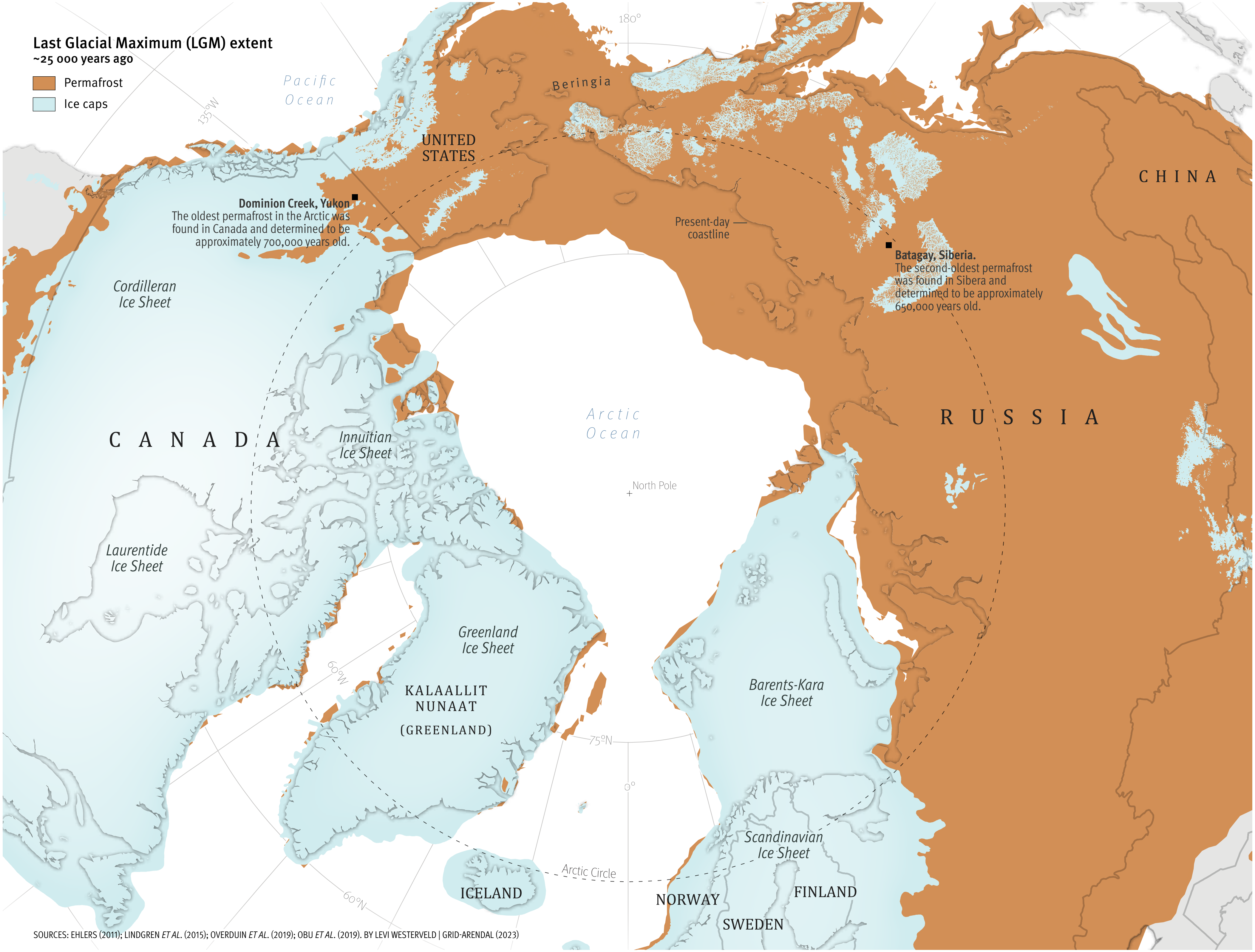
Pingo-like features also occur offshore in some shelf areas of the Arctic Ocean. Superficially similar to terrestrial pingos, they typically measure less than 30 metres in height and 300 metres in diameter. The formation of offshore pingo-like features is related to liquid and gas flow driven by permafrost thaw or the decomposition of gas resulting from marine transgression across a permafrost landscape.

Taliks are areas of unfrozen ground within permafrost. Even in the winter, this material does not freeze. This may be due to local thermal anomalies, such as heat storage in surface waters (rivers, lakes, etc.) which keeps the material underneath unfrozen, or to mineralised groundwater flowing through permafrost. In the continuous permafrost zone, taliks are often found under thermokarst lakes and rivers that do not freeze all the way to the bottom.

Thermokarst is an erosional process whereby the thawing of permafrost leads to the settling, collapsing, or slumping of the ground when excess ground ice, such as ice wedges, melts. Approximately 3.6 million square kilometres, or 20 per cent, of the northern permafrost region is covered by thermokarst landscapes.

Numerous landforms are associated with thermokarst regions. Thermokarst lakes and ponds are found over much of the Arctic landscape, formed in depressions created by the thawing of ice-rich permafrost. They are important ecosystems, providing valuable habitat for many Arctic species. As the permafrost below continues to thaw, these lakes may drain and disappear, as part of the thaw-lake cycle. Other typical thermokarst landforms include retrogressive thaw slumps, erosion gullies, and active layer detachment slides. They occur in hilly terrain, when erosion hits ice-rich permafrost resulting in the retreat of a hillslope, or when water-saturated soils flow downslope.





SOURCES: EHLERS (2011); LINDGREN *ET AL.* (2015); OVERDUIN *ET AL.* (2019); OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Frozen in time

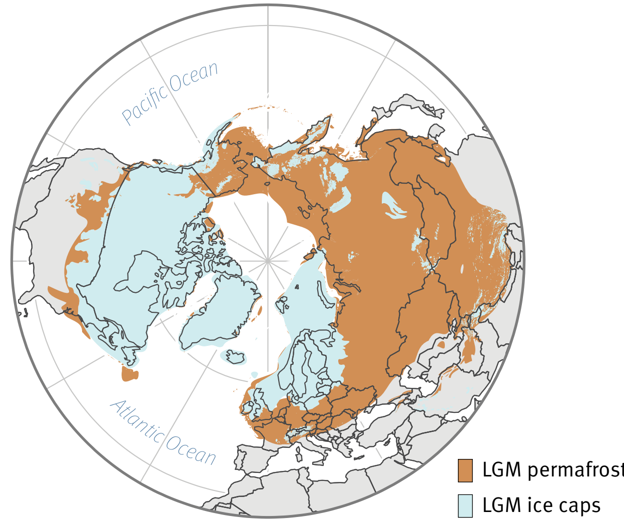
The history of permafrost

To understand modern permafrost, we must understand the conditions under which it formed and how they have changed. Although the oldest permafrost on Earth likely formed 2.4 million years ago, most permafrost found today was formed during or since the last ice age which ended about 12,000 years ago. Since then, the Earth's climate has alternated between cold glacial periods and warmer interglacial periods affecting the occurrence, distribution, and thickness of permafrost.

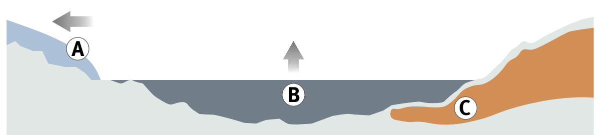
The Last Glacial Maximum (LGM), the time when ice sheets were at their greatest extent in the most recent geological past, occurred approximately 23,000 to 19,000 years ago in the northern hemisphere. At that time, the sea level was about 125 metres below current levels and ice sheets covered about 32 per cent of the Earth's total land area (compared with 10 per cent today). Permafrost likely reached its maximum spatial extent (the Last Permafrost Maximum) in the northern hemisphere towards the end of the last ice age.

Subsea permafrost formed during periods of glaciation when the sea level was much lower. In the Beringia region during the LGM, for example, the lower sea level exposed large areas of the continental shelf forming a land bridge between North America and Asia. The very cold climate created deep and cold permafrost beneath the exposed land. With the onset of warmer conditions, the ice caps receded, and the sea level rose again, submerging the land bridge. The cold bottom water of the Arctic shelves and ice in the sediment has allowed this permafrost to persist for over 10,000 years after being submerged. As a result of warming from seawater above and geothermal heat flux from below, subsea permafrost has been slowly thawing since it was flooded.

Glacial isostatic adjustment (GIA) plays a critical role in determining the rate of local sea level change and the presence or absence of both subsea and saline permafrost. GIA is the rebound of the Earth's crust after the retreat of large ice sheets. Land that was covered by large ice caps at the end of the last ice age (e.g., much of Scandinavia and the Canadian Arctic Archipelago), is emerging today. Subsea permafrost is absent in these areas. In contrast, where the land was free of ice (e.g., extensive stretches of the Arctic Coastal Plain in western North America and Eurasia), vast areas of terrestrial permafrost were created and subsequently flooded by the sea, leading to the occurrence of subsea permafrost. Additionally, the influence of GIA on hydrology, temperature, and topography can alter the accumulation and distribution of salt and the formation of frozen ground leading to the occurrence of saline permafrost.



Last Glacial Maximum (LGM). Ice caps and glaciers cover large parts of the northern hemisphere, especially in North America and Scandinavia. Permafrost is present in other areas, especially Asia.

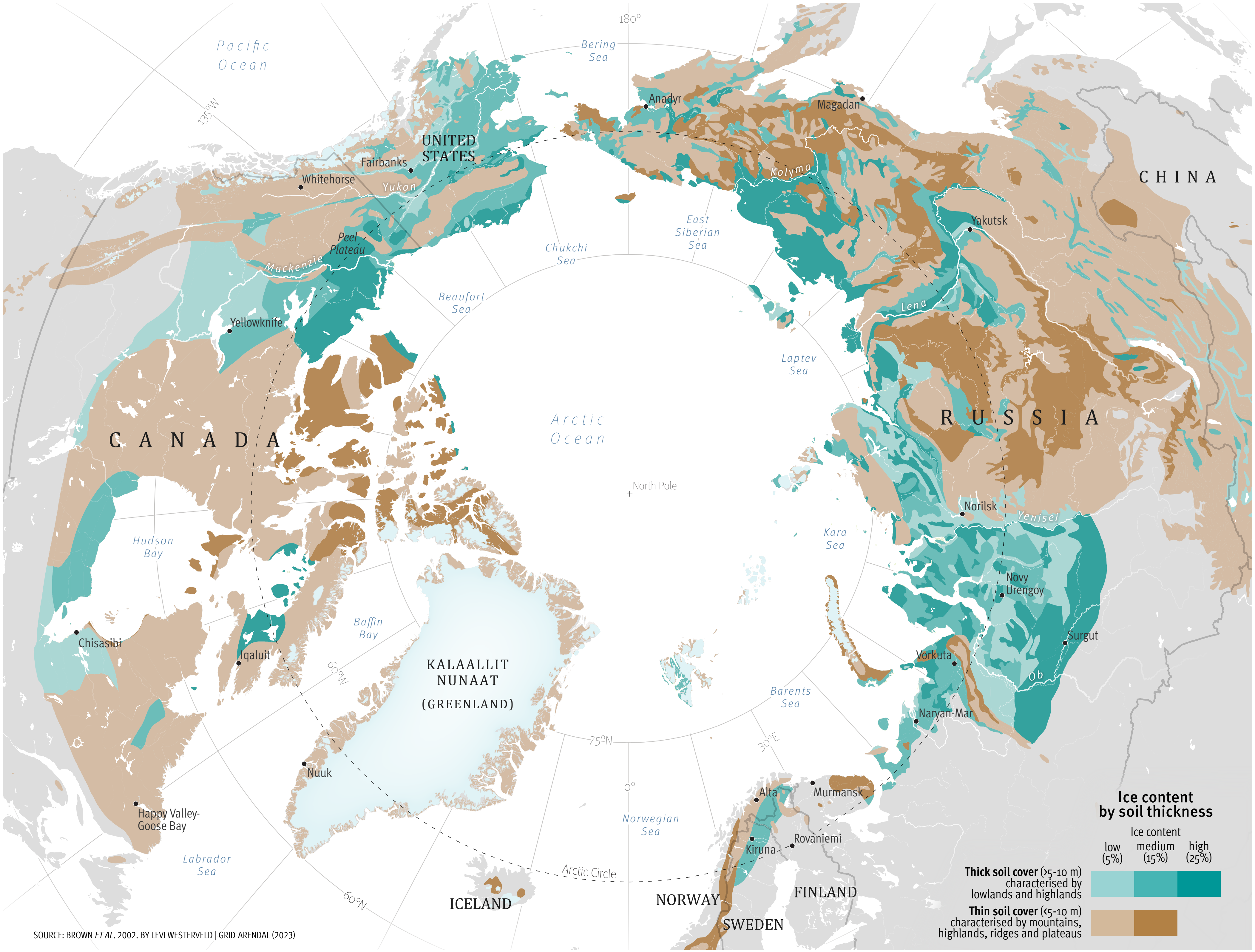


As temperatures rise, ice caps and glaciers retreat (A) resulting in sea level rise (B). Rising seas floods terrestrial permafrost to create susbsea permafrost (C).

Present day. Ice caps and glaciers continue to melt. Climate change drives the degradation and thawing of terrestrial, coastal, and subsea permafrost (D).

Change in temperature (° C) compared with the 1960–1990 average

SOURCE: JOUZEL *ET AL.* (2007). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



SOURCE: BROWN *ET AL.* 2002. BY LEVI WESTERVELD | GRID-ARENDAL (2023)

An icy balance
Arctic permafrost physiography

The way in which permafrost responds to atmospheric warming depends on numerous factors including local soil properties, topography, hydrology, and ground-ice content. A dry organic rich surface layer insulates the ground and can delay thawing, particularly if the permafrost is rich in ground ice. On the other hand, bedrock is a much better conductor for heat, so permafrost in rocky areas responds much faster to warming.

Landscape features such as hills and valleys affect ground temperatures and therefore influence permafrost processes. The temperature of sloping ground depends on its steepness and aspect (orientation towards the sun). In the northern hemisphere, steep south-facing slopes absorb more heat than gentle slopes or slopes that face north. Likewise, on the leeward side of a slope, snow may linger longer than in exposed locations. Snow acts as insulation, keeping the ground warmer rather than cooling it down. Flat depositional landscapes are more prone to the formation of thermokarst lakes while areas with greater relief are more susceptible to slumping and erosion.

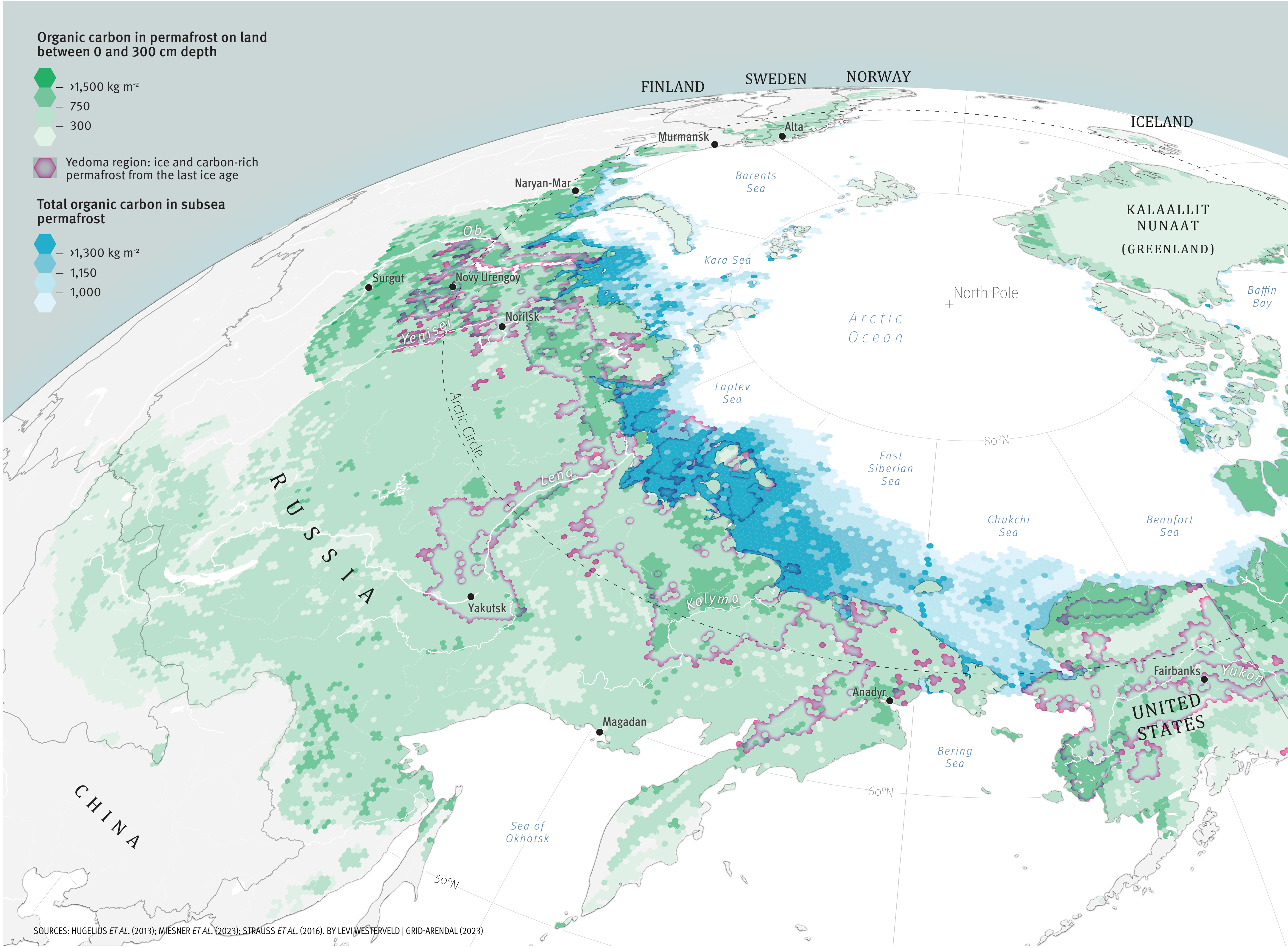
Ground ice refers to ice that forms in freezing and frozen ground. Ground-ice content has a tremendous influence on permafrost thaw, with considerable differences between ice-rich permafrost (i.e., permafrost containing large amounts of ice) and ice-poor permafrost (i.e., permafrost that contains little or no ice). The melting of excess ground ice leads to surface subsidence and the formation of ponds and lakes, a process known as thermokarst. In ice-rich permafrost, increased rates of thermokarst development can impact hydrology, ecology, and biogeochemistry as well as infrastructure such as buildings and transportation routes, while in areas with less ice, the effects will be smaller

As the Arctic climate warms and permafrost thaws, the landscape may be subject to great changes, especially in areas with ice-rich permafrost. When ice-rich permafrost thaws, hillsides may collapse resulting in “retrogressive thaw slumps”. The thawed sediment becomes saturated with meltwater and starts sliding downhill, where it can threaten infrastructure. If it enters nearby waterbodies, the increased sediment can make the water cloudier and affect aquatic ecosystems. If a thaw slump reaches the margin of a lake, it may rapidly drain as the water runs over the headwall of the slump.

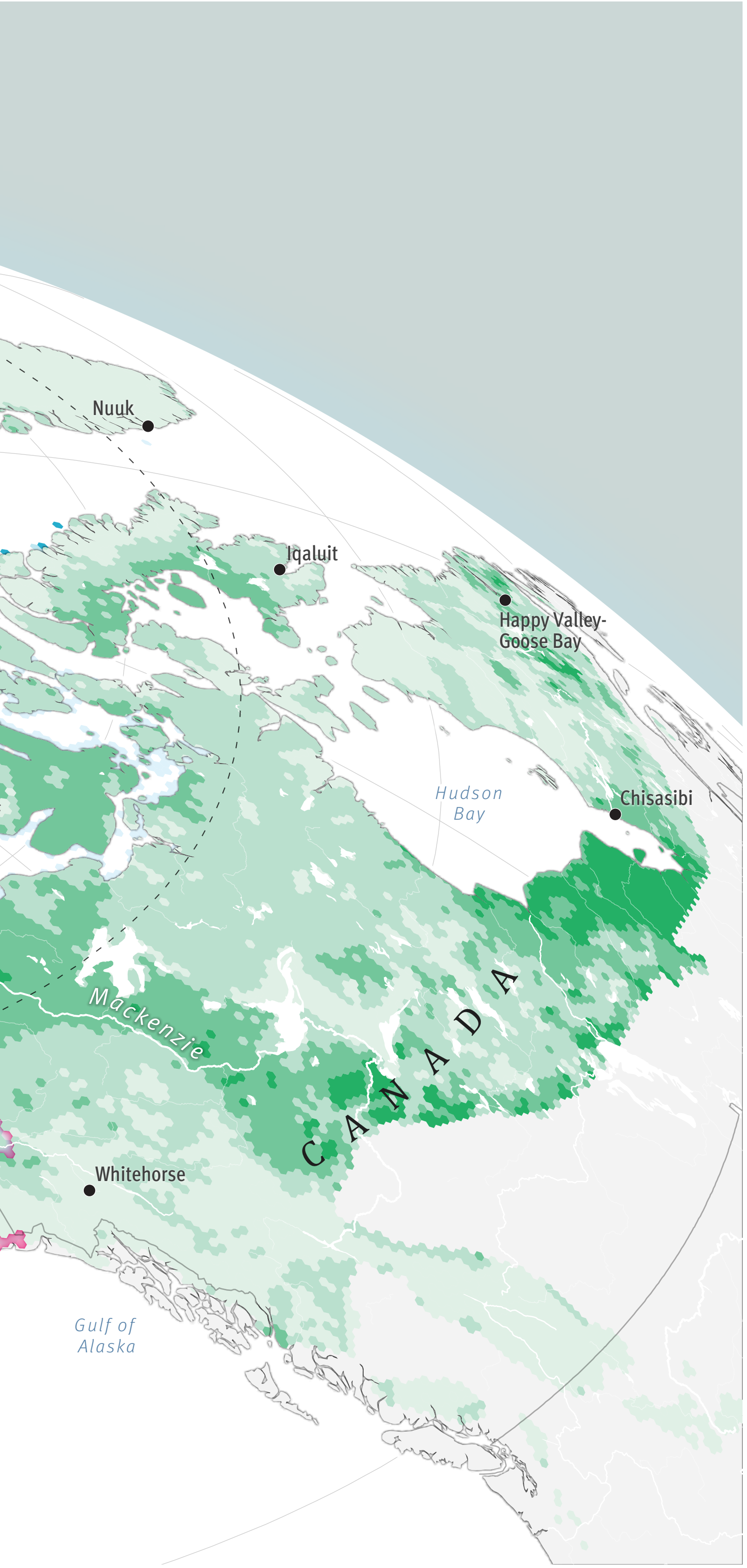
The Peel Plateau in Canada’s Northwest Territories may be experiencing some of the most dramatic changes in North America. A rugged landscape with many fast-moving streams combined with ice-rich permafrost is resulting in large-scale landscape changes as the ground ice melts and summer precipitation increases. As ice-rich sediment in the upper permafrost is exposed to thawing, the ground subsides, exposing more permafrost to warming and releasing sediments into nearby waterways and eventually reaching the Arctic Ocean. These processes are happening around the Arctic wherever there is ice-rich permafrost.

Although the appearance and disappearance of thermokarst lakes is not uncommon, the overall trend is towards a decrease in their number. Thermokarst lakes may drain because of the presence of taliks, areas of unfrozen ground in the permafrost that connect to the groundwater underneath, or due to the erosion of drainage channels. As the Arctic warms, thermokarst lakes and shallow lakes without thermokarst origin may become more common in the continuous permafrost zone, while they may disappear in the discontinuous zone and in lake-rich coastal plains.

Also characteristic of some permafrost landscapes are ice-wedge polygons, which form when frozen ground shrinks and cracks. These cracks occur in a polygonal pattern and the resulting ice wedges grow to form a honeycomb pattern across the tundra. As the climate continues to warm, the ice wedges may melt and the polygon centres may be emptied of water. Over time, this can lead to a draining of the landscape and further ground subsidence. In low-lying coastal areas, ice-wedge polygons will become flooded by sea level rise or by rising waters in rivers.



SOURCES: HUGELIUS *ET AL.* (2013); MIESNER *ET AL.* (2023); STRAUSS *ET AL.* (2016). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



What lies within

Organic carbon in permafrost

As long as permafrost stays frozen, the organic carbon within it will remain locked in the ground. But when permafrost thaws, microorganisms become active and start to break down the organic matter releasing greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Methane and nitrous oxide are relatively short-lived but very potent greenhouse gases, while carbon dioxide is much more abundant and can persist in the atmosphere for thousands of years. As the climate warms, the thickness of the active layer (the seasonally thawing layer) increases, accelerating microbial decomposition and increasing greenhouse gas emissions. This in turn stimulates further global warming and permafrost thawing in a positive feedback loop.

Arctic permafrost soils are among the largest carbon stores in the world. Even though near-surface permafrost soils represent only 15 per cent of the total global soil area, they contain almost one-third of the world's soil carbon. Permafrost soils contain almost twice as much carbon as is currently found in the atmosphere. The surface layer (0–3 metres deep) contains 65–70 per cent of the total permafrost soil carbon, while another 25–30 per cent of permafrost carbon is stored at depths greater than 3 metres. The Yedoma region of Siberia and Alaska, which remained ice free during the last glaciation, has rich carbon stores in deep, thick deposits. Additional permafrost soil carbon, less than 10 per cent of the total, is contained in Arctic river deltas.

Subsea permafrost also contains carbon, both as organic carbon frozen in the permafrost and as gas, either in pockets of free gas or trapped in gas hydrates. Most of the gas found in this setting is methane. Though the amount of organic carbon stored in subsea permafrost is poorly understood, it is likely to be considerable, as permafrost extends as deep as 700 metres in some places.

Gases may be prevented from escaping into the atmosphere by layers of overlying permafrost and seawater. However, warming temperatures, increasing stormy weather, and decreasing sea ice have led to rising water temperatures at the sea floor. As the overlying subsea permafrost thaws, methane and other gases may find new pathways to escape through the sediment into the water and then to the atmosphere. Whether and how quickly this ends up increasing greenhouse gas concentrations in the Earth's atmosphere is still being studied.

To understand how permafrost is changing over time, scientists monitor the thickness of the active layer, the amount of groundwater in it, and the temperature of the ground. Measurements taken over many years provide valuable information on how permafrost may be changing and offer insights into its future. Together with satellite observations and laboratory experiments, as well as computer modelling, scientists are building a more complete picture of permafrost and its changes across the Arctic.

Many questions remain unanswered about permafrost thaw and greenhouse gas emissions. Researchers continue to work on getting better estimates of the amount of carbon in permafrost soils and in subsea permafrost; how much and how quickly permafrost will thaw under different climate warming scenarios; how much carbon will be released into the atmosphere from thawing soils, and how much methane, carbon dioxide, or nitrous oxide will be released..

SOURCE: MODIFIED FROM VIEIRA *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

When ice grows up

Pingo Canadian landmark

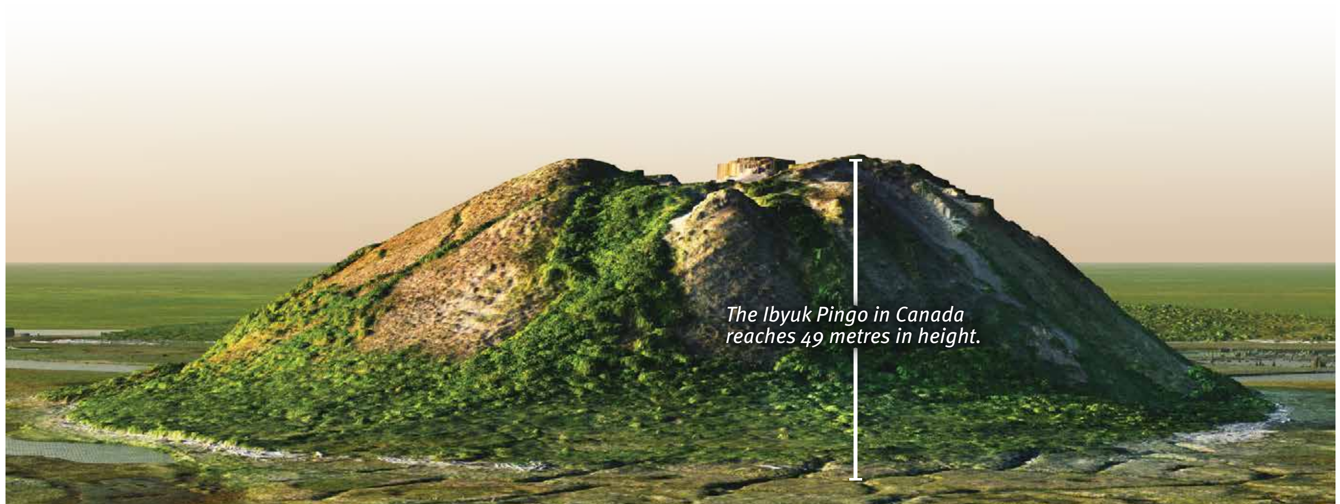
The greatest concentration of pingos in the world – about 1,350 – is found on the Tuktoyaktuk Coastal Plain in the western Canadian Arctic. In 1984, the Government of Canada formally designated 16 square kilometres of this region as the Pingo Canadian Landmark. Eight pingos are found within this unique protected area, including Ibyuk Pingo.

Standing at 49 metres in height and 300 metres across its base, Ibyuk Pingo is the tallest in Canada and second tallest in the world after the Kadleroshilik Pingo in Alaska which is 54 metres tall. Like most pingos, Ibyuk Pingo grew in a drained lake bottom and is cored by massive ground ice. Ibyuk Lake existed more than 12,000 years ago but probably drained less than 2,000 years ago.

Ibyuk and the other pingos of this region have served as the basis of scientific research for over 50 years but they also carry cultural significance for Indigenous Peoples. The word "pingo" itself comes from the local Inuit language, Inuvialuktun, and means "small hill". The first recorded use of "pingo" in English was in 1938 by the Danish-Canadian botanist Alf Erling Porsild. The name "Ibyuk" is another Inuvialuktun word meaning "two mounds which are close together" and was how local Inuit collectively referred to Ibyuk Pingo and another large pingo, Split Pingo, located to the north of Ibyuk.

Ibyuk is estimated to be about 1,300 years old. Observations show that the upper part was still growing at approximately 2 centimetres per year in the 1980s. At the top is a crater that formed when the overburden at the summit collapsed. The bottom of the crater contains a small pond, which recent observations show may have drained.

All pingos reach their maximum height within several centuries but are also susceptible to erosion. Although still growing, Ibyuk is starting to show signs of collapse. There is already evidence of slumping and erosion on its slopes, giving the appearance that it is splitting into two parts.



SOURCE: MODIFIED FROM VIEIRA *ET AL.* (2019). BY ALEX TAIT & LEVI WESTERVELD | GRID-ARENDAL (2023)

Drilling down

Learning the secrets of permafrost

Scientists use a range of techniques to study permafrost and how it responds to changing environmental conditions. Core sampling is a technique used to provide information on the vertical distribution of organic matter, ice, and sediments in permafrost landscapes. The corer consists of a long hollow tube screwed into the ground to remove long cylinders, or cores, of permafrost material (sediment, rock, soil, etc.). In the lab, the samples can be analysed for their physical properties, chemical composition, microbial content, age, and other characteristics.

Ground-based measurements using cores are the only way to measure the vertical distribution of ground-ice content, which is critical to developing an accurate understanding of the effects of climate change on permafrost. As temperatures increase, ground ice in the upper layer of permafrost melts, eventually leading to soil subsidence. The sinking ground affects both human settlements and infrastructure (roads, electric poles, pipelines) which were originally built upon solidly frozen ground. As the ground thaws, organic matter that had been stored in permafrost for millennia is broken down by microbial activity and released into the atmosphere as carbon dioxide, methane, and nitrous oxide, which furthers warming. Thawing permafrost also contributes to further climate warming.

The Yukon coastal plain is an example of an area with particularly ice-rich permafrost. Core samples taken here, however, reveal a great variability in ground-ice content in different deposits, with the highest ice content found in moraines and the lowest in glacio-fluvial deposits. More accurate measurements help scientists to better forecast the impacts of climate warming on subsidence, erosion, and the mobilisation of organic carbon in different landscapes.

In addition to core sampling, scientists also conduct continuous, long-term monitoring of ground temperature in boreholes to understand the changes occurring in permafrost. The first systematic observations of permafrost temperature started in the 1930s in eastern Siberia. Early investigations were performed manually and required multiple measurements each day. This meant that researchers could only carry out transient monitoring studies at research stations. Over time, technology evolved, and it is now possible to monitor a range of permafrost parameters (e.g., temperature, active layer depth, moisture content) year- round, either manually or remotely (see graphic on changing permafrost temperatures in section 2.1).

Permafrost temperature is commonly measured using temperature sensors installed in boreholes drilled into the permafrost. Boreholes are classified according to their depth: surface (less than 10 metres), shallow (10–25 metres), intermediate (25–125 metres), and deep (greater than 125 metres). The use of data loggers (small automated digital recording devices) in the boreholes reduces the need for site visits to take measurements. There are now networks of boreholes for long-term permafrost temperature monitoring across the Arctic and in other permafrost regions around the world. As of 2015, there were 1,074 boreholes in the Global Terrestrial Network for Permafrost, with the greatest numbers in Russia (294), United States/Alaska (201), and Canada (194). The oldest borehole in the network is in Russia, drilled in 1957 to a depth of 85 metres.

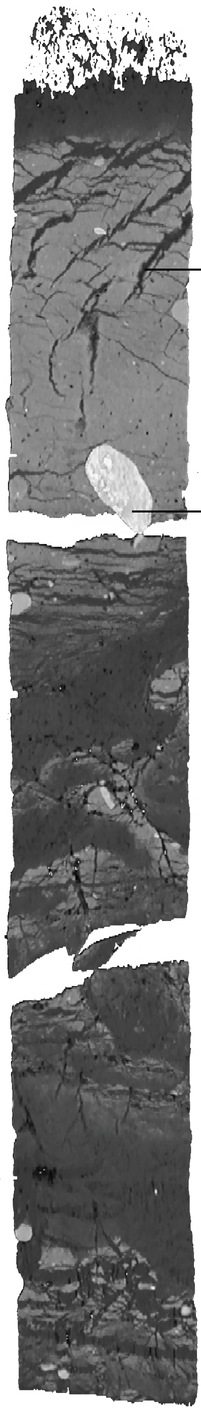
***Permafrost core** taken in the spring of 2019 from the Yukon coastal plain. The core was taken to explore the distribution of organic matter, ice, and sediments in permafrost.*

The top of the permafrost core is composed of frozen and decomposing organic matter that form a ~6 centimetre-thick brown layer.

The horizontal stripes are an artefact of the coring technique which involves screwing a metal tube into the soil.

This sample is limited to 60 cm because the coring technique could not penetrate the harder, rocky underlying soil.

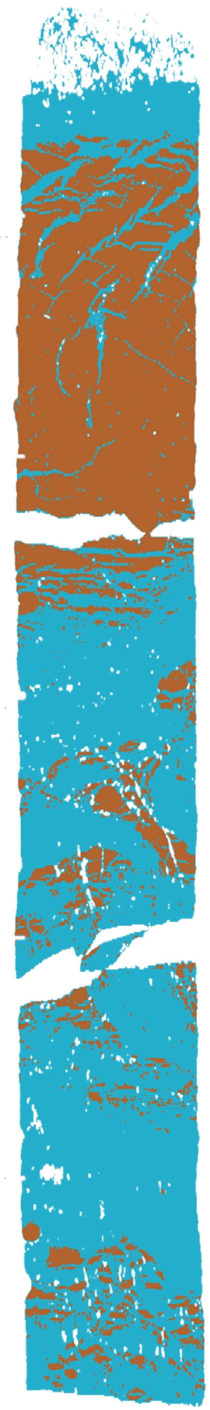
SOURCE: PIKA *ET AL.* (IN PREP). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Computed tomography (CT) scan *A CT scan is similar to an X-ray used by doctors in hospitals. It allows permafrost researchers to see inside the permafrost without breaking it apart.*

Darker stripes show ice interveined in the sediments.

Dense objects, such as this 3 centimetre-long pebble, appear brightest on the CT scan of the permafrost borehole.



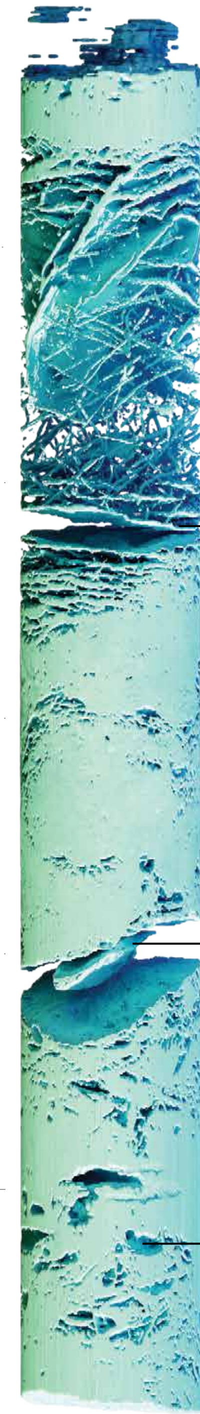
Classified CT scan *Sediments in orange (frozen mixture of mostly minerals and organic material with pore ice) and ice in blue (mainly ice, mixed with a small amount of sediment). This allows permafrost researchers to calculate their respective overall contributions.*

The top 22 cm of this borehole is the active layer. It undergoes seasonal thawing cycles and hosts plants and organisms which live and grow through the warmer spring and summer months.

Permafrost table

Ice
Sediment

Ice dominates these deeper layers of the permafrost. But smaller pebbles and denser sediments (orange) are present throughout the core.



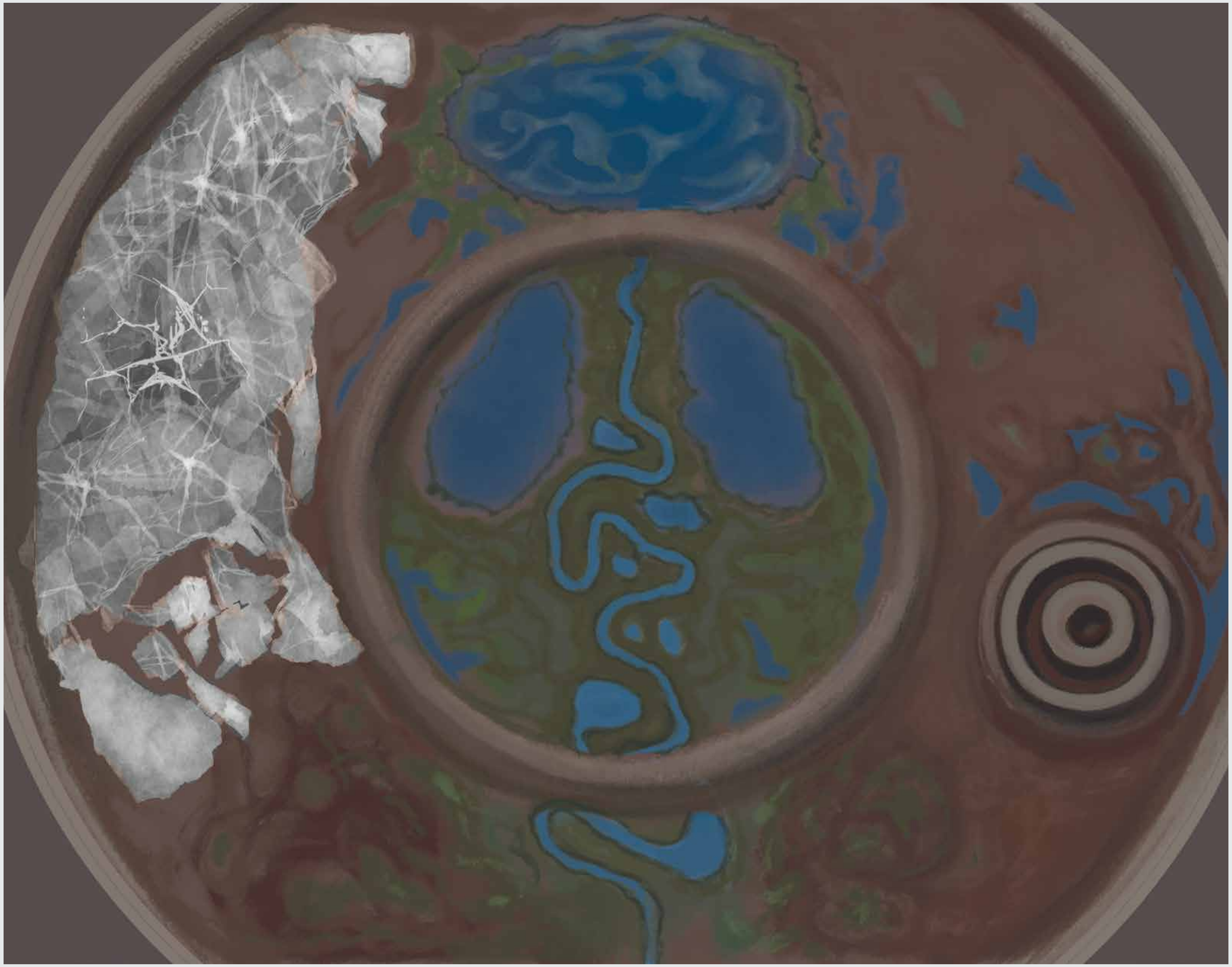
3D Visualisation *This 3D visual of the core shows mainly the excess ice content, including ice-rich sediments. Visualising the data this way helps scientists better understand the structure of the core and the history of the landscape it was taken from.*

The structure of ice veins is visible a the top of the core.

Lens-like structure of ice visible about and below the core break.

This suspended ice lens occurs right at the break between the second and third core segment.

These holes in the core are filled with sediments.



PORTRAIT CEO AND SENIOR SCIENTIST AT B.GEOS GMBH, AUSTRIA

Annett Bartsch

Since my school days, I've been interested in the Arctic, drawn in by stories of the vast cold landscapes and research expeditions there. As a geography student, I travelled to Svalbard where I gave presentations about permafrost and geomorphology to other students. Today, I'm a remote sensing specialist, leading international projects and finding novel ways to use satellite imagery to analyse permafrost in the Arctic.

One of the main challenges of mapping permafrost from satellite imagery is that permafrost is a sub-ground phenomenon. But despite this, there are different ways imagery can be used to help map and study permafrost thaw. First, land surface temperatures can help model the presence of permafrost. Second, land surface features associated with permafrost can be seen and analysed on imagery. The mass of lakes across the Arctic, for example, are the result of permafrost thaw. Permafrost can also be monitored from space by analysing ground subsidence and upheaval, which are also tied to soil properties: the more ice in the ground, the greater the change at the surface over a season. An added challenge of mapping landscape features is the very frequent presence of clouds in the Arctic. Scientists like me make use of radar satellite data which can see through the clouds, but this type of data is still expensive and hard to obtain at a very high resolution.

In the summer, I spend many nights in Siberia or Scandinavia sleeping in tents and collecting field measurements. These measurements help connect what is measured on the satellite images with what is happening on the ground. Collaboration with local experts is very important. In Siberia, we work with Russian scientists who often have camps next to boreholes that contain instruments to measure permafrost. Nowadays, drones are also used to close the gap between satellite imagery and field observations.

One of the main goals when applying remote sensing to permafrost studies is to improve climate models and to assess the impacts of permafrost thaw. Permafrost is thawing across the entire Arctic and the implications are complex, both locally and globally. With remote sensing alone, we can make very interesting maps, as we've done in recent work mapping all infrastructure found within 100 kilometres of the Arctic coastline. But if we want to answer the big questions, we need to go one step further. For this, you need specialists from different fields to work with remote sensing experts, including Earth climate modellers and field specialists, that have a good understanding of local processes.

Many questions remain open, but technology has already come a very long way in helping to answer them. During my studies, it was very difficult to get access to data, and the resolution was very poor compared with today. Now, there is so much data that it's challenging to find the methods to process everything. It requires a lot of computing power. We need artificial intelligence and machine learning to deal with these data, which in the coming years will be central to cloud computing.

Un/settled
Life on frozen ground

Humans have lived in the Arctic for thousands of years, adapting to life in this harsh environment and passing their knowledge on to successive generations. Today, approximately 5 million people reside in the Arctic circumpolar permafrost area, the area defined by the northern circumpolar permafrost extent within the eight Arctic nations. Communities within this extent are known as permafrost settlements. There are currently 1,162 permafrost settlements in the Arctic. Almost 90 per cent of them have less than 5,000 inhabitants, but most people in this region, approximately 4 million, live in the larger 123 settlements that range in population size from 5,000 to 360,000. Most of the large settlements, 85 per cent, are found in the Russian Arctic.

The greatest number of permafrost settlements, over 65 per cent of them, are in the sporadic permafrost zone, in the southern part of the permafrost region. Unless situated directly on permafrost, these communities may not be immediately affected by permafrost thaw, but all of them will be affected by the changes occurring in the surrounding environment. Settlements in the continuous and discontinuous permafrost zones may experience significant impacts as the underlying permafrost degrades because of climate change. This includes Yakutsk and Norilsk, two of the largest settlements in the Arctic with a combined population of 486,000.

Constructing long-lasting, stable structures on permafrost is a major challenge since permafrost is increasingly neither permanent nor stable. As human activity expands in the Arctic and as global warming continues, it becomes more important to understand how infrastructure may be affected and how it can be made more resilient. Building on frozen soils can cause the underlying permafrost to thaw and sink, resulting in damage to buildings. This can result in anything from minor cracks in the walls to major structural failure. Transportation infrastructure – roads, airstrips, railways, bridges, etc. – is also subject to significant damage from permafrost thawing. Engineering solutions, such as building road embankments that allow heat to escape, are required. In areas that are too wet for roads, people only drive on winter ice roads that are built on frozen marshes or on frozen lakes and rivers. The thick ice can support very large trucks bringing equipment and supplies to communities and industrial operations. These roads are seasonal and need to be rebuilt every winter; and as the climate continues to warm, they are becoming less reliable and shorter lived.

Unlike in other areas, most of the groundwater in permafrost is frozen. In areas of discontinuous permafrost, it may be possible to drill through unfrozen ground to reach groundwater. In areas of continuous permafrost, however, drinking water often comes from lakes, rivers, or melting ice and snow. Some communities build insulated and elevated water pipes to supply running water to their homes.

Industrial operations (e.g., mining, oil, and gas exploration) also require special considerations to prevent the permafrost from thawing. The deep wells required for oil and gas may be lined with cement to prevent them from collapsing, while the equipment at the surface can be built on concrete pads. Because the oil must be kept above 60 °C to allow it to flow, pipelines are often built above ground so as not to thaw the permafrost and risk damage to the pipes.

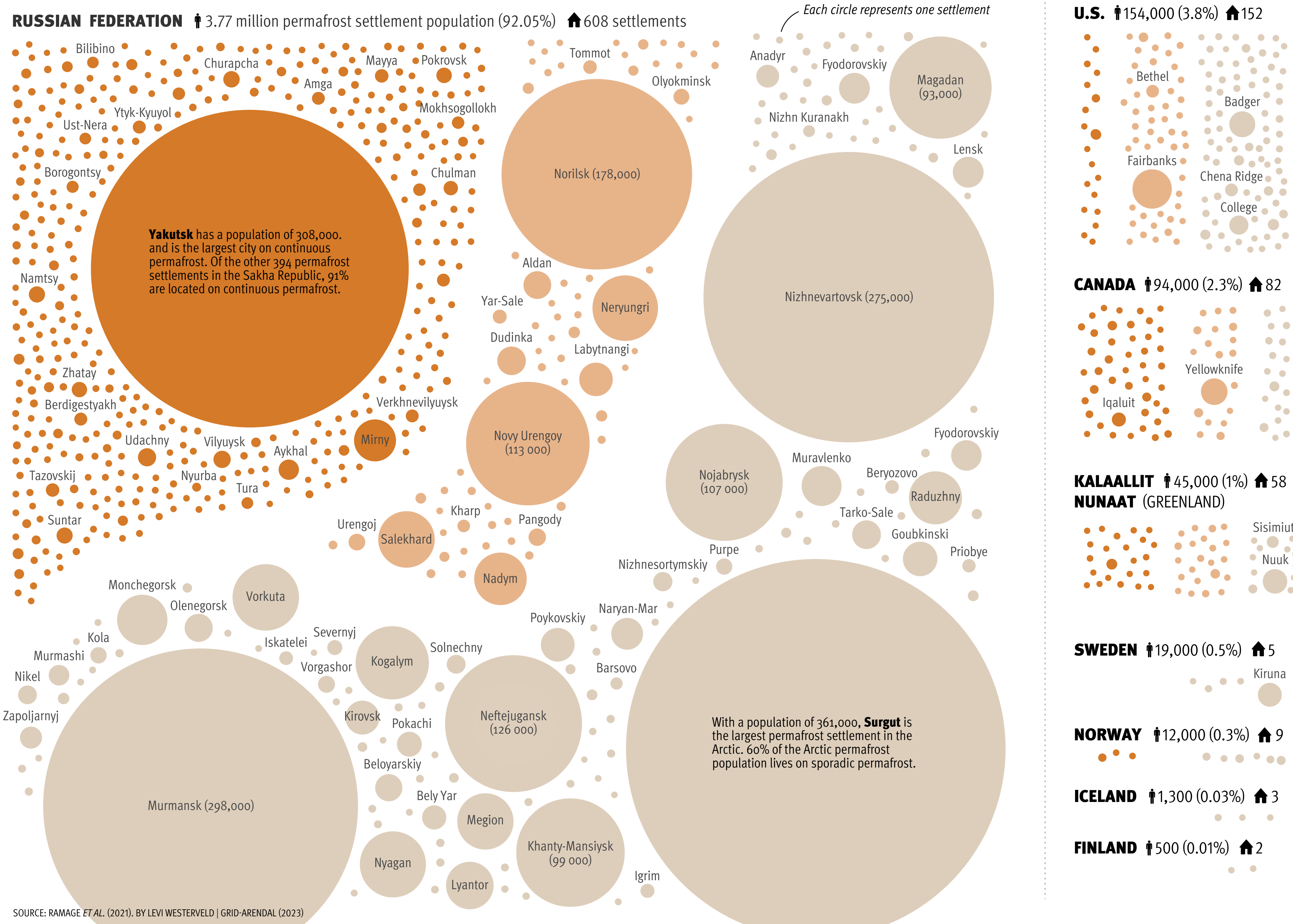
Indigenous Peoples and local communities depend on permafrost for more than just stabilising buildings and other infrastructure. Many still live traditional or semi-traditional lifestyles, where they depend on hunting, fishing, and gathering to support themselves, their families, and their communities. Knowing and understanding the characteristics of permafrost are vital for these needs. Reindeer herders, for example, rely on their knowledge of permafrost to determine how quickly the passage of their herds will turn the surface to mud. This determines where the herders will establish their camps, how long they can stay, and what herding operations they can perform. The effect of permafrost on the local landscape and vegetation also plays a role in influencing reindeer behaviour.

People also use permafrost as a nature-based solution for preserving food. For thousands of years people have harnessed the stable sub-zero temperatures of permafrost and built underground cellars in which to store fish and game. These traditional ice cellars are dug into the upper permafrost below the active layer with a doorway to protect the entrance area from warm summer air and discourage the accumulation of insulating snow in the winter.

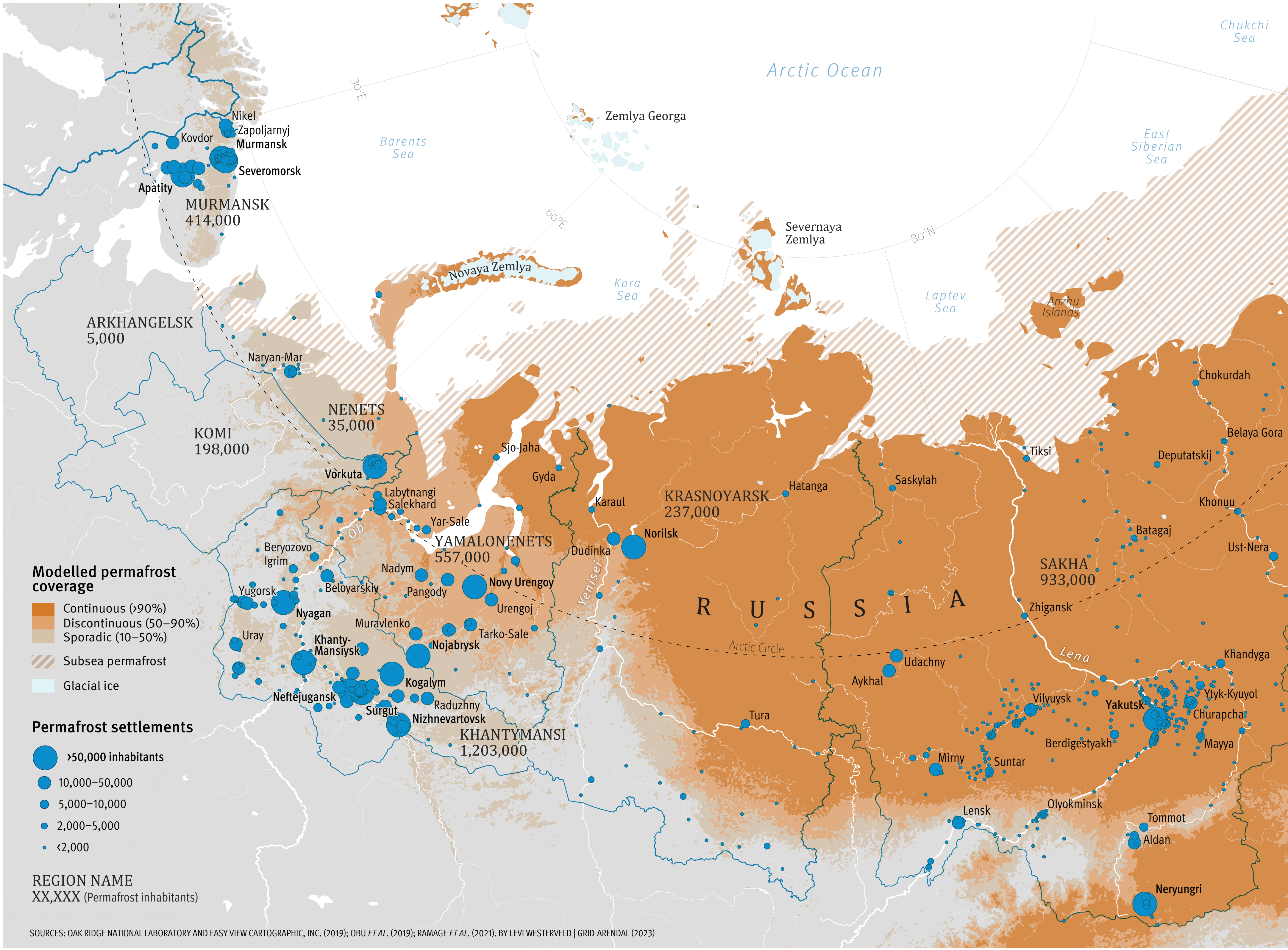
Arctic permafrost settlements

Continuous Discontinuous Sporadic

NOTE: Only settlements with a population over 5,000 are labelled.



SOURCE: RAMAGE *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



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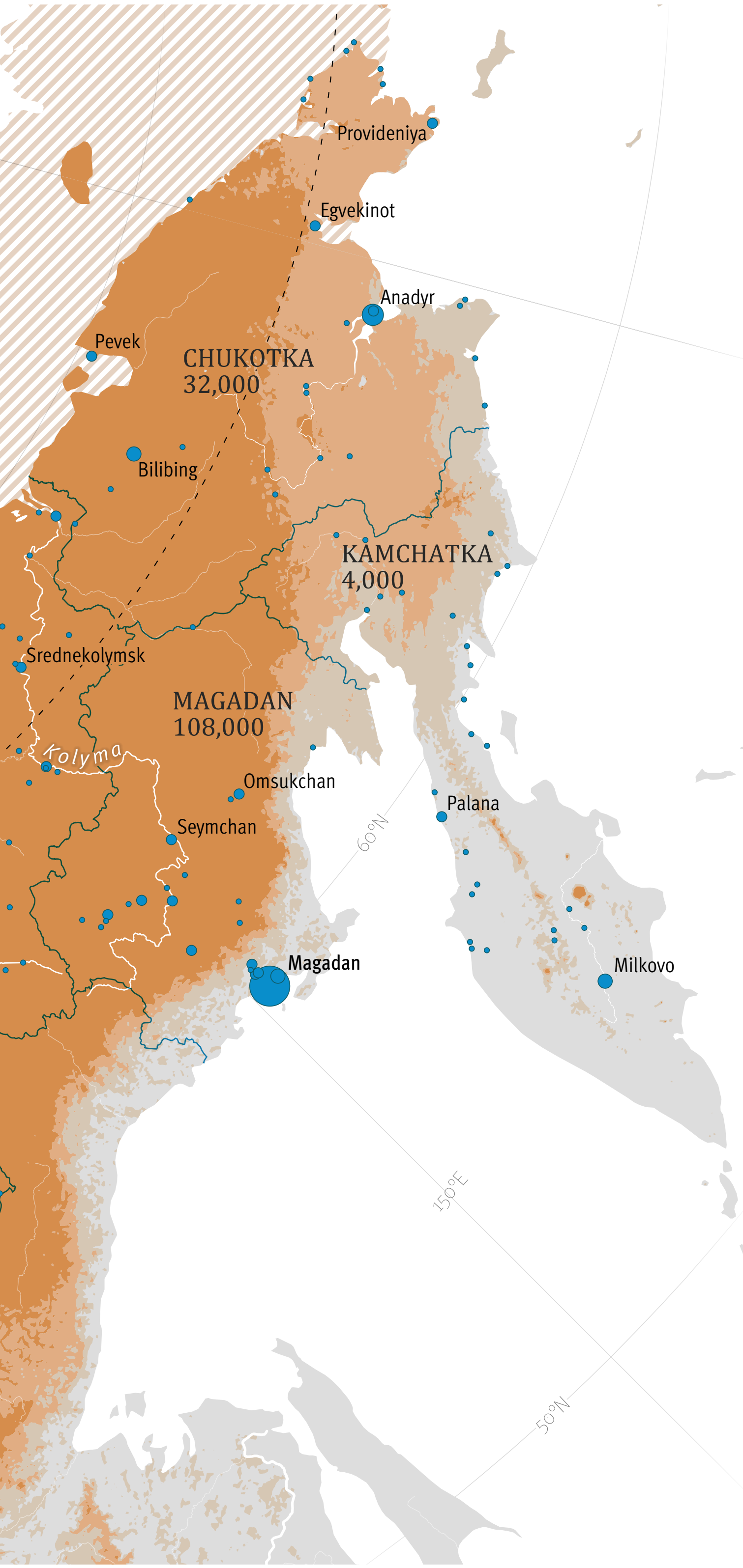


Frozen states I

Russian Federation

Most of the permafrost in the Arctic is found in Russia. Approximately 65 per cent of the country is underlain by permafrost, mainly in the continuous zone. Russia encompasses 85 per cent of the Arctic's large permafrost communities, i.e., those with 5,000 inhabitants or more.

In contrast to most other parts of the Arctic, most Russian permafrost settlements are inland and on continuous permafrost. Of the 713 permafrost settlements, 401 are in the continuous zone, 241 in the sporadic zone, and 71 in the discontinuous permafrost zone.

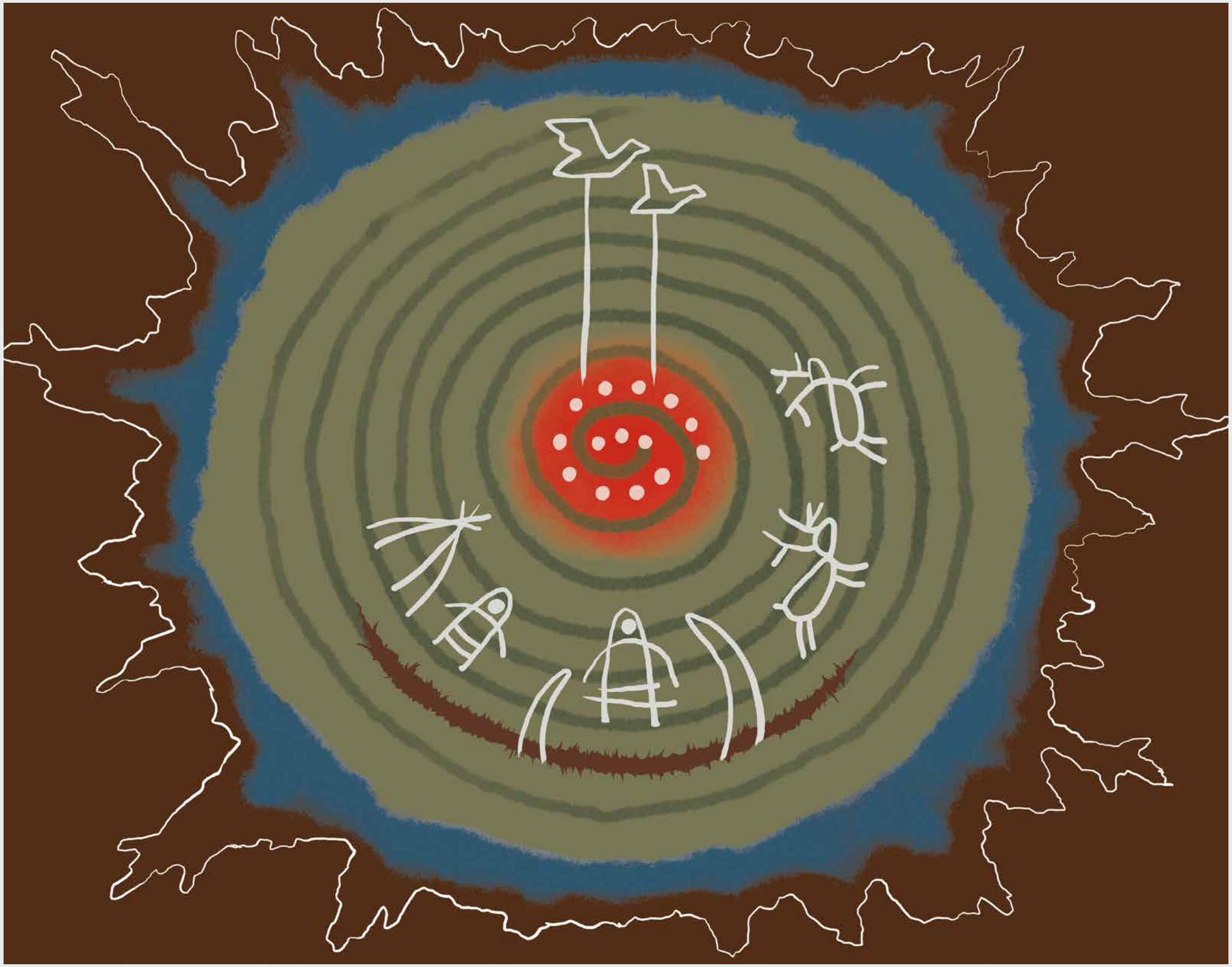
Forty distinct groups of Indigenous Peoples live in the North, Siberia, and Far East of Russia. The largest of these are Dolgan, Nganasan, Nenets, Saami, Khanty, Chukchi, Evenk, Even, Enets, Yupik, and Yukagir. Many continue to rely on the traditional activities of reindeer herding, fishing, and hunting.

Of the estimated 2.2 million domesticated reindeer in the Arctic, 1.5 million are in Russia. The main reindeer herding areas are in Yamal-Nenets, Sakha Republic (Yakutia), and Chukotka. The Nenets people are thought to be the largest group of nomadic reindeer herders in the world. Almost half of the Nenets people (approximately 20,000), continue to herd reindeer today. Reindeer herders are often nomadic, moving with their herds from winter pasturelands in the forest tundra/northern taiga zone to the midsummer pasturelands on the coast of the Arctic Ocean. Each group of herders may tend to anywhere from hundreds to thousands of reindeer.

The seasonal changes caused by the thawing and freezing of the ground influences the activities of the reindeer herders. In some areas, the thawing of the active layer in the summer can turn the ground to a semi-liquid mud layer, making travel difficult and even dangerous for both herders and reindeer. This sludge layer can occur from both natural causes and human or animal activity, such as trampling. By "reading" local conditions, experienced herders can determine the likelihood of this phenomenon occurring and move their herd to safer ground.

The permafrost landscape also influences travel. Landforms such as ice-wedge polygons must be traversed at the correct angle to avoid breaking the sledge. Likewise, the narrow ravines created on hillsides or riverbanks by permafrost thawing and sliding are used by herders to climb up and down steep slopes in a safer manner.

Herders also use their knowledge of the landscape and vegetation – both of which are influenced by permafrost processes – to monitor and predict the behaviour of their reindeer, moving them to desired locations as required. Similarly, the different waterbodies in permafrost landscapes also influence the movements of herders and their animals. Thermokarst lakes are important to herders, who believe them to be cleaner than other sources of water for drinking. These lakes also help to cool the reindeer and escape insects in the summer.



PORTRAIT CHAIR OF COUNCIL OF YUKAGHIR ELDERS, NELEMNOYE, RUSSIA

Vyacheslav Shadrin

I was born in 1967 in the village of Nelemnoye in the Upper Kolyma region of the Sakha Republic (Yakutia). I am both a researcher focusing on the history and culture of Indigenous minorities of the Russian North, and the Chairman of the Council of Elders of the Yukaghir people. My role as Chairman means I travel a lot, visiting communities across the Russian Arctic.

Permafrost underlies 80 per cent of Yakutia, including my home village of Nelemnoye, which is located just below the Arctic Circle in an open, subtundra forest. This Yukaghir village is composed of 40 buildings situated a few hundred metres west of the Yasachnaya River, a tributary of the Kolyma River. About 300 people live in the village, 200 of which are Yukaghir, an Indigenous Peoples group from north-east Asia. According to the latest population census, only 1,603 Yukaghir remain today.

Changes in climate limit our traditional fishing and hunting practices. Autumn sea-ice fishing, which historically would start around the end of October, can no longer take place, or has become very dangerous, as any ice is still quite thin then. Hunting practices have been similarly affected. Musk deer hunting usually takes place in November when the animals migrate from their summer to winter pastures. But as the ice road is no longer accessible this early, traditional hunting grounds are impossible or very dangerous to access. Hunting that occurs later in the winter is less profitable, as the quality of fur is lower.

Reindeer herding, an important livelihood among traditional communities in the Arctic, is also affected by permafrost thaw. The lowlands are wetter and muddier, and reindeer sometimes lose weight and get ill. Herders are also increasingly dependent on technology such as GPS to find their way. Thirty or forty years ago, it was impossible to imagine that a herder could get lost; they knew the tundra extremely well. Losing their traditional knowledge makes them more vulnerable.

Traditionally, underground cellars dug in the frozen ground are used to store meat, fish, and berries. Now, these underground freezers are thawing due to the warming climate. Many are collapsing and no longer in use. They are being replaced with refrigerators, but these require constant electricity and are vulnerable to power outages. I estimate that 80 per cent of the diet of inhabitants in Nelemnoye now consists of food bought in shops. In my youth, only goods such as sugar, salt, and tea were bought from shops; the rest was harvested from nature. Cases of diabetes are increasingly frequent in northern Indigenous communities. We are victims of this system. We do not choose this lifestyle.

As the number of fishers and hunters dwindle, more people are now scavenging for mammoth tusks and bones, which can fetch high prices on the black market. These appear at the tundra's surface as permafrost thaws. But scavenging mammoth tusks is against traditional beliefs. Traditionally, we associate mammoths and their spirits with the underworld. Bad things come from there. In the past, remains of mammoths mostly appeared during floods and on eroding riverbanks, so they are associated with such events. When these tusks and bones resurface in the tundra, a door is opened between the underworld and the middle world where people live.

Politicians and scientists always talk about the need to develop adaptation strategies. But these aren't for us. It is our life, our everyday. We live in these conditions, and we are adapting all the time. For Indigenous Peoples, climate change is a real threat that brings about many challenges which impact our traditional livelihoods and lead to fewer people being involved in traditional activities.

Frozen states II

North America

In North America, the Arctic circumpolar permafrost area encompasses the state of Alaska in the United States of America and Yukon, Northwest Territories, Nunavut, Nunavik, Nunatsiavut, and southern Labrador in Canada. Approximately 80 per cent of this region is underlain by permafrost. It is dominated by continuous and discontinuous permafrost in the western Arctic and the Arctic Archipelago, while sporadic and isolated permafrost are becoming more prevalent in the eastern Arctic and interior of Alaska.

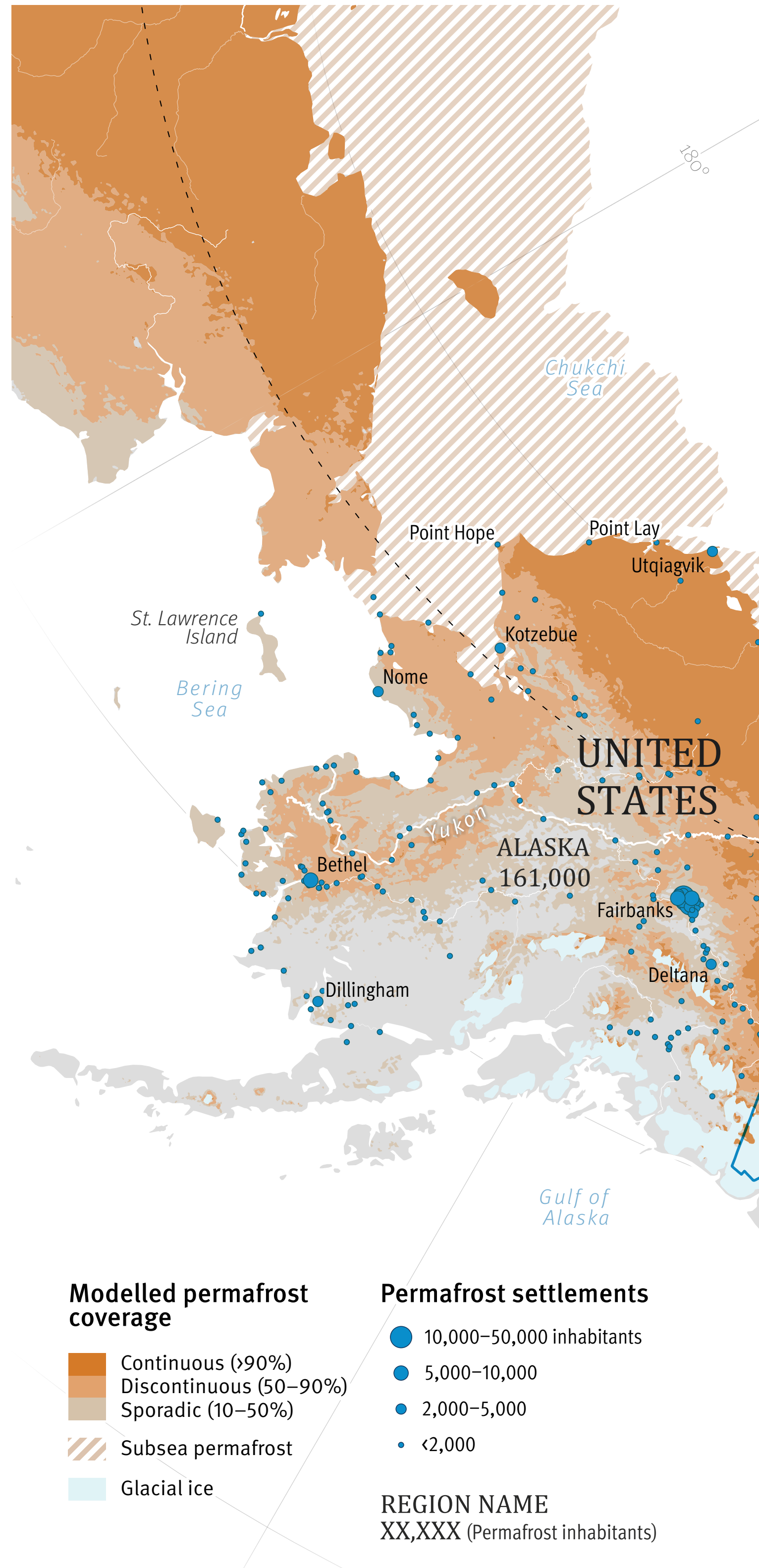
Of the 300 permafrost settlements in the Canadian and Alaskan Arctic, 63 are in the continuous permafrost zone, 69 are in the discontinuous zone, and 168 are on sporadic permafrost. Almost half the settlements in this region are situated on the coastline and most of these are on continuous permafrost. While many Indigenous Peoples rely on subsistence hunting and fishing, resource extraction from mining and oil and gas development are important economic activities in both countries.

Permafrost creates unique challenges for the many communities in this region. Permafrost coastlines are exposed to high rates of coastal retreat due to longer periods of open water along the coast, warmer summers, and increased frequency and intensity of storms. Coastal communities, especially those in the western Arctic, are affected by erosion and subsidence, which affects local infrastructure, land cover, and cultural sites.

More than 20 communities in Canada and Alaska have already been declared threatened because of coastal erosion. In Shishmaref, Alaska, the rate of coastal erosion is so high that the inhabitants have voted to move the town to a new location on the mainland. In the Hamlet of Tuktoyaktuk in the Northwest Territories (Canada), some houses deemed most at risk from collapsing into the Arctic Ocean have been moved further inland at significant cost. The hamlet is now implementing a plan to slow erosion, but eventually, the community will need to consider relocation.

Industrial and military facilities and critical community infrastructure along the western Arctic coast of North America are also threatened by accelerating coastal erosion and storm surges. Like all structures in the Arctic, they were designed for stable permafrost conditions but now many show signs of instability because of increased thaw settlement and seasonal frost heaving. Many will face costly retrofits if they are to remain viable in the future. Numerous sumps, designed to contain contaminants such as drilling mud in permafrost at former oil and gas exploration wells in the Mackenzie Delta region, are now unstable or collapsing, allowing toxic fluids to escape.

Subsea permafrost occurs offshore of the western Canadian and Alaskan Arctic, as well as off northern Eurasia. While there is currently limited offshore development, there is considerable potential for large-scale oil and gas development in the future. Knowledge about the distribution and properties of subsea permafrost is still limited and more research is required to ensure the safety of operations in this environment.



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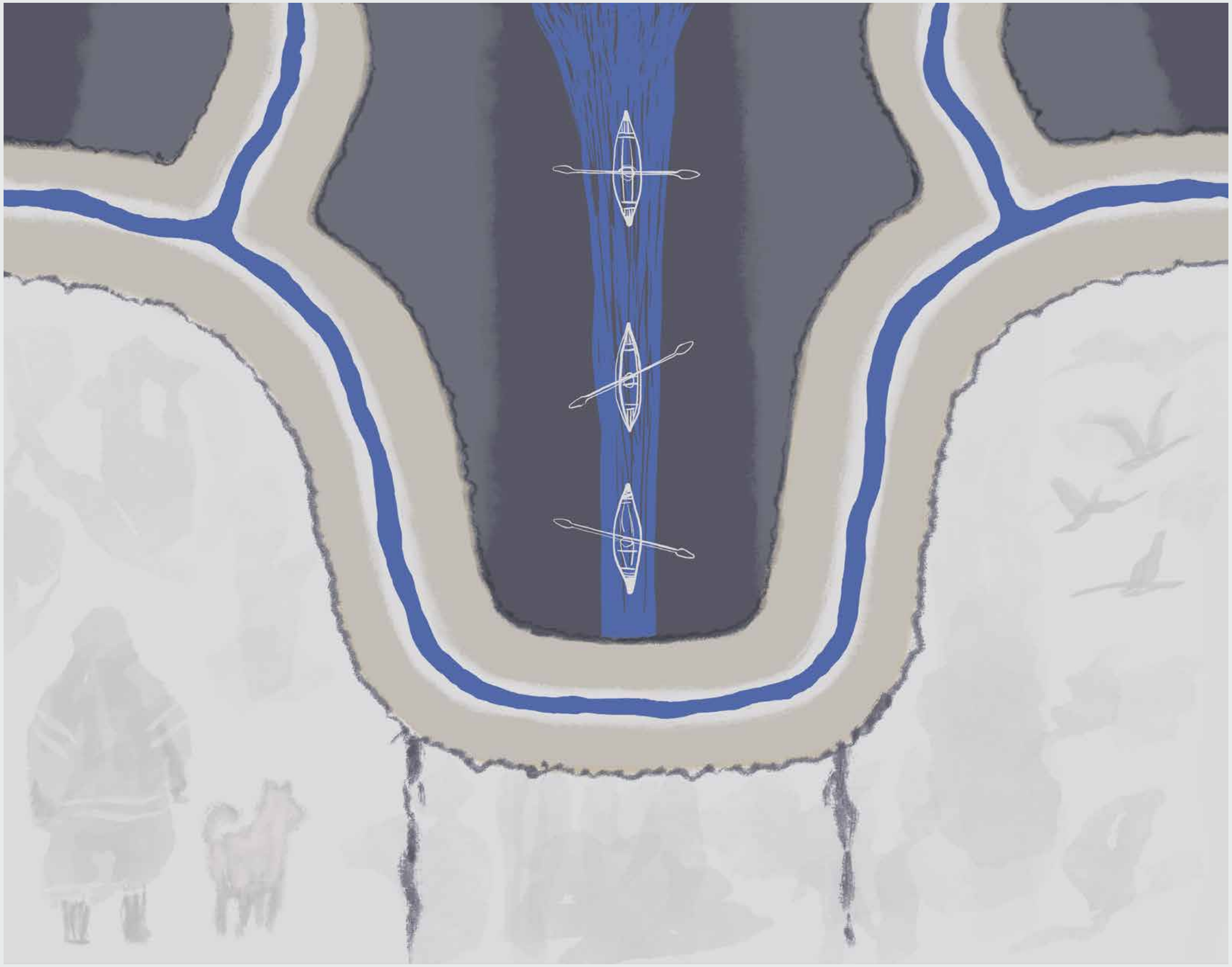

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PORTRAIT ENVIRONMENTAL COORDINATOR AT GWICH'IN RENEWABLE RESOURCES BOARD, AKLAVIK, NWT CANADA

Jessi Pascal

I would describe myself as independent, family oriented, and a lover of the outdoors. I have three siblings and we live in Aklavik, a hamlet with a population of approximately 500 located in the Inuvik region of the Northwest Territories, Canada. I recently moved back to Aklavik from Inuvik – the administrative centre of the Inuvik region – located approximately 50 kilometres east of Aklavik.

I would describe Aklavik as a community where everyone knows everyone, and where everyone helps each other. That's what I like most about Aklavik. The village is situated along the Peel River [Peel Channel of Mackenzie Delta], providing our community with all the water we use for drinking, showering, and washing. During the winter, it is cold and white. The mountains to the west are absolutely beautiful. A lot of people rely on wood stoves as a heat source, including my folks, because purchasing oil for the furnace is quite expensive. I haul wood for them whenever I can.

Spring is the time for goose hunting and carnivals. Each community in the Mackenzie River Delta has these carnivals, which include attractions like snowmobile races, dog sled races, and egg toss competitions. These were cancelled in 2021 due to COVID-19. In the summer, many people including my family go fishing, either in the Peel River or down at Shingle Point in the Arctic Ocean. In the fall, a lot of people hunt rabbits, either in the fields or over on the delta. There is always something happening.

One of my first encounters with permafrost was when my dog was digging in the ground and suddenly reached the frozen permafrost table. I wasn't very familiar with what permafrost was when I was a kid. But I thought it was pretty interesting, that a dog could just dig a couple of feet and suddenly bump into it!

Being located on permafrost means Aklavik has had to adapt in many ways. None of the pipes, for example, are underground. We get our sewage removed by a vehicle that comes in. All the buildings are built fairly high off the ground to protect them from flooding. But due to permafrost thaw, a lot of infrastructure is at risk. Recently we had to borrow some jacks and bumped my father's house to make it level again.

There is no road to get in or out of Aklavik. Instead, boats are used in the summer as a mode of transportation across the Mackenzie Delta. In the winter, snowmobiles and trucks can be driven on the ice road. But with climate change, these landscapes are changing. I go out with my friends to check our traps and it is really cold out, and then suddenly we are sinking in slush. It's very unpredictable. I am not sure if it is directly related to permafrost.

Reflecting on the impacts of permafrost thaw on my community, it's clear that people here know very little. It wasn't part of my high school curriculum, for example. I feel it is not treated as a priority for people to know about. I have interviewed many people as part of my work with the Joint Secretariat of the Inuvialuit Settlement Region about topics such as permafrost, fish, animals, weather, and so on. But the subject I've had most trouble with is permafrost. This is a subject that folks know and have heard about, but don't understand its science aspect and how it affects our lives. I think a little more education on the topic would be beneficial for our community. After all, it is literally right under our feet.

Frozen states III
Nordic region

Permafrost in the Arctic's Nordic region is found in Kalaallit Nunaat (Greenland), Iceland, in the northern parts of Norway (Nordland, Troms, Finnmark), Svalbard, Sweden (Norrbotten), and Finland (Lappi). There are 149 human settlements in this region, most located in the sporadic permafrost zone. Only Kalaallit Nunaat and Svalbard have settlements in the continuous permafrost zone (23 and 2 settlements, respectively), while only Kalaallit Nunaat has settlements in the discontinuous zone (22 settlements). All permafrost settlements in Kalaallit Nunaat and Svalbard are coastal.

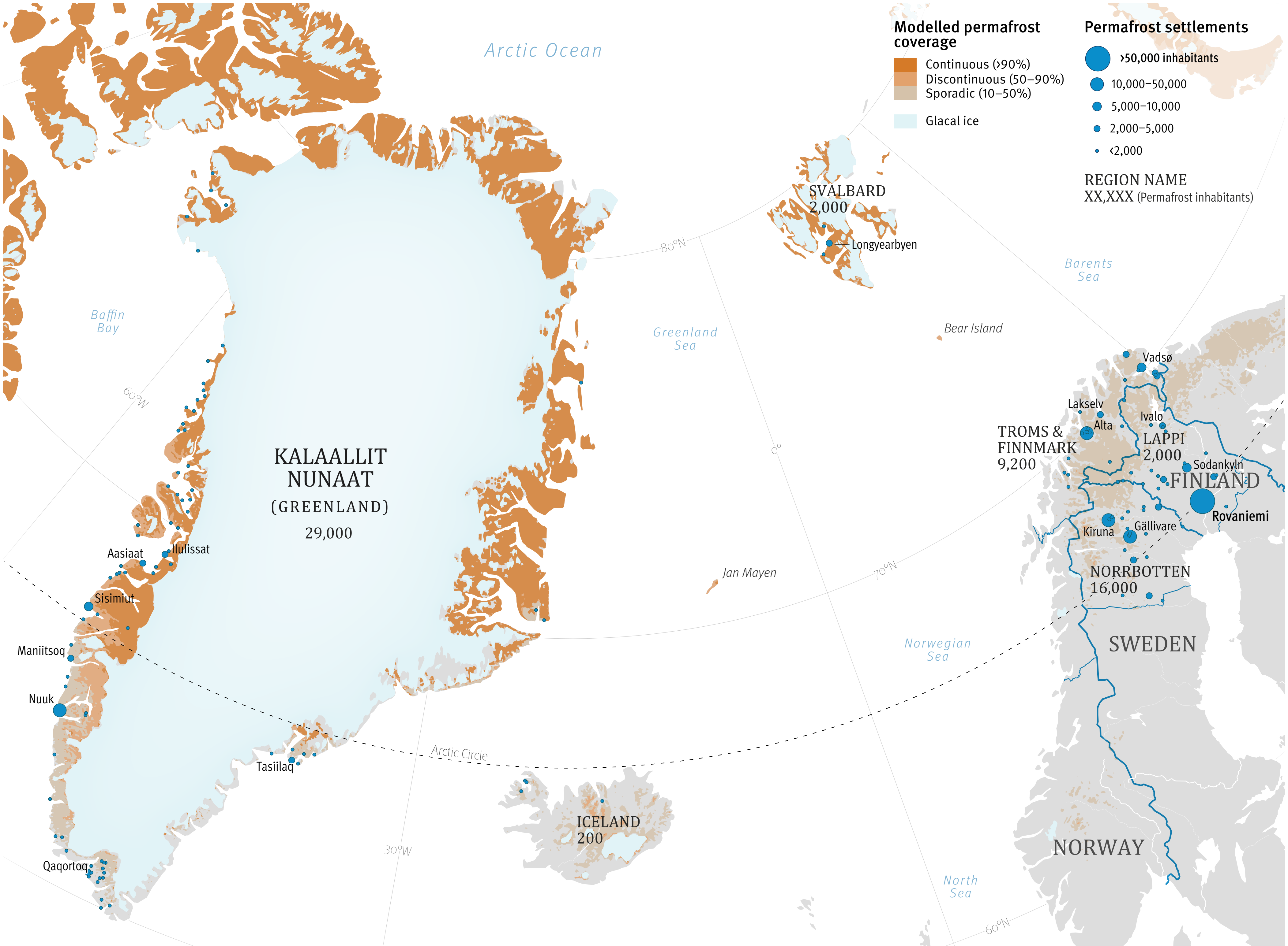
Although geopolitically part of Europe, Kalaallit Nunaat is geographically and geologically part of North America, and as such shares many characteristics with the eastern Canadian Arctic. As in the eastern Canadian Arctic, many homes here are built on bedrock, meaning they are unlikely to be destabilised by permafrost thaw and so are less vulnerable to collapse than sedimentary and ice-rich permafrost sediments. Other infrastructure, however, is often found on vulnerable permafrost. The area between the parking lot and runway at Kangerlussuaq airport has been severely affected by permafrost thaw. Damage to the surrounding community infrastructure, especially the road networks, has also been reported.

North-east Kalaallit Nunaat is home to the Zackenberg Ecological Research Operations, a research station established in 1995 with the goal of facilitating research into High Arctic ecosystems. Located 74 °N, the station is in the continuous permafrost zone with an active layer thickness of 20–100 centimetres. The remote location was believed to be ideal for conducting long-term ecological studies of at least 50 years. Research here contributes to a range of international programmes, including numerous studies on permafrost. Now, as elsewhere in the Arctic, the research station itself is under threat. Permafrost thaw-related erosion along a nearby riverbank has intensified. Now, rather than lasting 50 years, some buildings may need to be moved or rebuilt soon to avoid collapse.

The Svalbard archipelago is part of Norway but in many respects is a world away from it. Situated midway between mainland Norway and the North Pole, this remote archipelago was largely unpopulated until the first settlements – small outposts – started appearing in the 1600s. Today fewer than 3,000 people live on Svalbard. Like Kalaallit Nunaat, Svalbard is also an important location for permafrost research in the Nordic region of the Arctic. Permafrost thickness in Svalbard ranges from less than 100 metres in low-lying areas to more than 500 metres in the high mountains. Extensive permafrost monitoring takes place on Svalbard, and long-term observations of the active layer thickness and permafrost ground thermal regime are included in the Svalbard Integrated Arctic Earth Observing System.

Svalbard's permafrost also plays a vital role in helping protect the world's food supply. The Svalbard Global Seed Vault is built into the permafrost on a mountainside. The vault provides for the long-term storage of seeds from around the world, backing up plant genetic diversity in the case of disease or other disaster. Rather than a hindrance, the permafrost was considered an added benefit of the site because it would aid in preserving the seeds.

Although there is significantly less permafrost in southern Norway, it does exist in steep bedrock slopes, including at lower elevations on north-facing slopes. This area has been subject to more scientific study in recent years because of the increased frequency of rockfalls and rock-ice avalanches during hot summers. These occurrences can put both people and infrastructure at serious risk, either through direct impact or from associated events such as flooding.



SOURCES: OAK RIDGE NATIONAL LABORATORY AND EASY VIEW CARTOGRAPHIC, INC. (2019); OBU *ET AL.* (2019); RAMAGE *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

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PORTRAIT MAYOR OF AVANNAATA MUNICIPALITY, KALAALLIT NUNAAT (GREENLAND)

Palle Jerimiassen

To say it plainly: I love my job as mayor! When I get to work in the morning, I don't know what the day will bring. It's always something different, and new challenges emerge every day. Most of the work happens in front of the computer, working with different reports, future plans, and many meetings with different people. I have coffee meetings with the economic sector and soda meetings with young people. In politics, one must work to bring different opinions together. That is something I like to work with and something I think I'm good at.

Avannaata is a big municipality, the world's biggest, with 21 villages and four towns, and it's important that I am in contact with the whole population. There are rather big cultural differences within the municipality. Ilulissat is a multi-ethnic town with 5,000 people, and about 30–40 different ethnic groups. Up in the northernmost parts, in the Qaanaaq district, there are still communities that primarily live off hunting. The last village to get public electricity supply was two years ago. So, there are quite big differences in the way we live within the municipality, and I always have to think about how the decisions we take here in Ilulissat impact the people in other communities. It's all connected, and that's part of what makes it interesting.

Twenty years ago, some scientists came here and said that in 10 years' time there will no longer be ice in front of Ilulissat, but no one believed them, and neither did I. But I clearly see now that climate change has come to stay. I know that the fishers and hunters are very concerned about how the climate is changing, the unpredictable weather forecasts, and the changes that are happening in animal migration. It's something we all talk about daily because we base our whole lives on our surroundings.

Regarding infrastructure, we have many people complaining about the conditions of the roads, why their houses end up crooked, and why the sewage leaks. We are getting bigger and bigger challenges with climate change and permafrost thaw. The places where roads are built on permafrost become like the small roller coaster in Tivoli Gardens. The land around houses sinks and causes damage to their structures. Qaanaaq, for example, is built on land where the whole area has started moving. That means that everything becomes crooked. We've also had issues with the underground sewage system. Look at the old football pitch where sewage water started leaking out!

We must take climate change into account, we have to, especially up in the north where the whole way of life is completely changing. We made the United Nations Sustainable Development Goals a starting point for the municipality's development strategy. We have also considered permafrost in all our plans. In some places, new houses need to be built on bedrock. That's difficult in places like Qaanaaq where there aren't many suitable places around. We started with a road leading from Ilulissat to the new airport, but there have been challenges trying to figure out where to place the road on solid ground. In the future, we have to develop the sewage system above ground in places where there's permafrost so that we don't have the same issues we have in town now.

We get a lot of visits from all types of people. We say to them that we all must take responsibility. We are most impacted but even though we are only a small part of the whole world, we also have to take responsibility ourselves to reduce climate change.

Awakening Giant

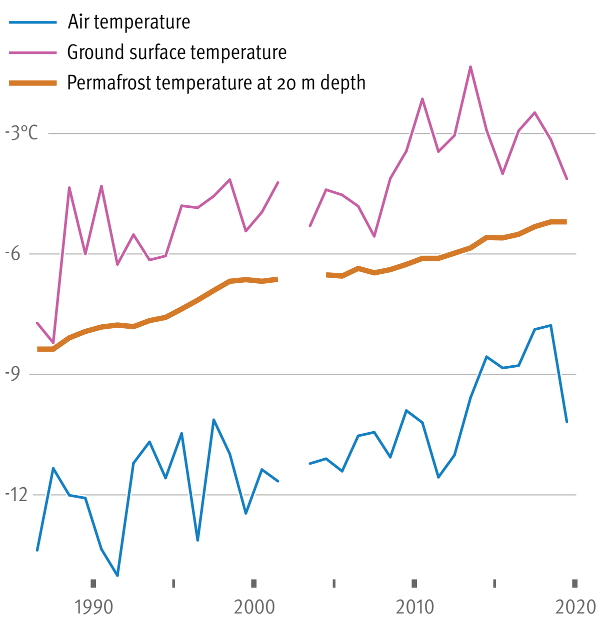
Permafrost and Climate Change

Warming up, warming down

Increasing ground temperatures

Permafrost is defined according to temperature: ground that remains at or below 0 °C for at least two consecutive years. Despite its name, permafrost is not permanent. Changes in the environment, both natural and human-caused/anthropogenic, may cause the ground temperature to rise above 0 °C, leading to permafrost thaw. Depending on the extent of the warming, permafrost thaw may trigger other environmental effects, including landscape changes and the release of greenhouse gases.

Temperatures at Deadhorse, Alaska
Mean annual values (° C) from 1987 to 2020



SOURCE: ROMANOVSKY, V. (2021). ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Permafrost temperature is linked to ground surface temperature, which itself is linked to changes in air temperature and snow cover dynamics. As the temperature of the permafrost surface (i.e., the ground below the seasonally thawed active layer) increases, it conducts heat to deeper permafrost resulting in warming at depth as well. One way in which scientists monitor temperature change in permafrost is through sensors installed in boreholes drilled into the ground. This can be just a few metres deep in warm permafrost to more than 20 metres in cold permafrost and bedrock. Long-term monitoring of borehole temperatures shows widespread evidence of permafrost warming across the Arctic in response to global climate change, with dramatic increases in some locations.

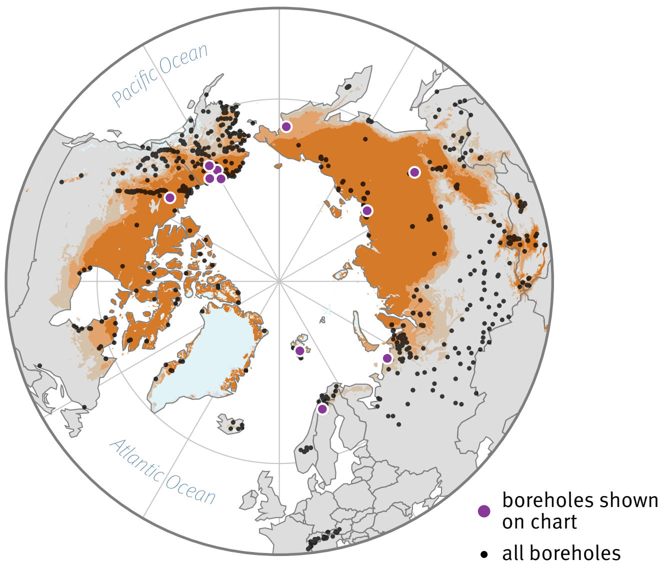
During the 2007–2009 International Polar Year (IPY), ground temperature measurements were made at 575 locations around the circumpolar Arctic. Although longer-term records exist in some places, the IPY initiative added many new monitoring sites to provide a more complete network across a range of permafrost locales. Collectively, these sites provide an important baseline against which to measure permafrost change across the Arctic.

Measurements since the IPY reference period show that annual mean permafrost temperatures are increasing at most sites across the Arctic. Between 2007 and 2016, ground temperature in the continuous permafrost zone has increased by 0.39 °C on average. The greatest temperature increase in individual boreholes within continuous permafrost was recorded at Marre Sale on the Yamal Peninsula in north-western Siberia (+0.93 °C at a depth of 10 metres) and on Samoylov Island in the Lena River delta in north-eastern Siberia (+0.95 °C at a depth of 20.75 metres). Within the discontinuous permafrost zone, ground temperature was found to have increased by 0.2 °C with the greatest increase in Magadan in the far east of Siberia (+0.95 °C at a depth of 10 metres).

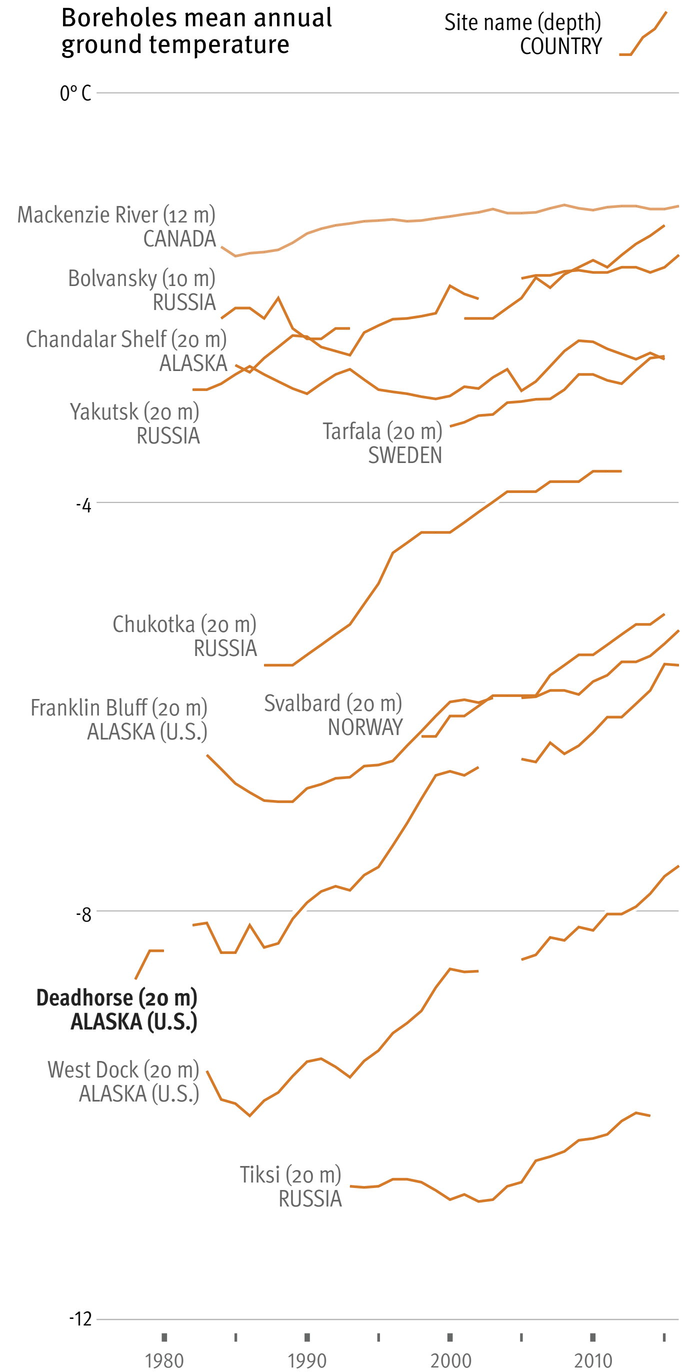
Permafrost can be described as either cold or warm, based on its temperature deep below the surface where it changes slowly from year to year. When cold permafrost, which is below -1 °C, is heated, it undergoes noticeable warming. In contrast, warm permafrost refers to permafrost with temperatures close to 0 °C. Within this type of permafrost, the presence of ground ice acts as a buffer against warming by absorbing heat and melting. However, once the ground ice has melted completely, the ground heats up and is no longer permafrost. The mountainous areas of Europe, as well as Central Asia and the Andes, tend to have warm permafrost that contains less ice.

The rate of permafrost warming is not uniform across the Arctic, varying according to local environmental conditions such as climate, snow cover, ground ice, vegetation, and organic layer thickness. The greatest changes have been observed in cold permafrost in the Arctic and High Arctic where warming may reach up to 1 °C per decade. While there have also been temperature increases in warm permafrost, these have been smaller, generally less than 0.3 °C per decade.

Warming permafrost has led to a global concern about the potential for the release of large amounts of greenhouse gases. Permafrost soils hold vast amounts



of organic material. When thawed, this material is exposed to microbial decomposition, producing either carbon dioxide, methane, or nitrous oxide. Current projections suggest that the combined release of carbon dioxide and methane from permafrost thaw will be equivalent to 100–200 billion tons of carbon dioxide by 2100. By comparison, global net greenhouse gas emissions from anthropogenic sources were equivalent to approximately 59 billion tons of carbon dioxide in 2019. The additional contribution from permafrost will make it even more difficult to limit global warming to 1.5 °C, as set out in the Paris Agreement of the United Nations Framework Convention on Climate Change. Warming permafrost can also bring about landscape changes such as erosion and landslides which impact natural ecosystems, traditional lifestyles (e.g., hunting and fishing), and built infrastructure.



SOURCE: BISKABORN *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

The chill is gone

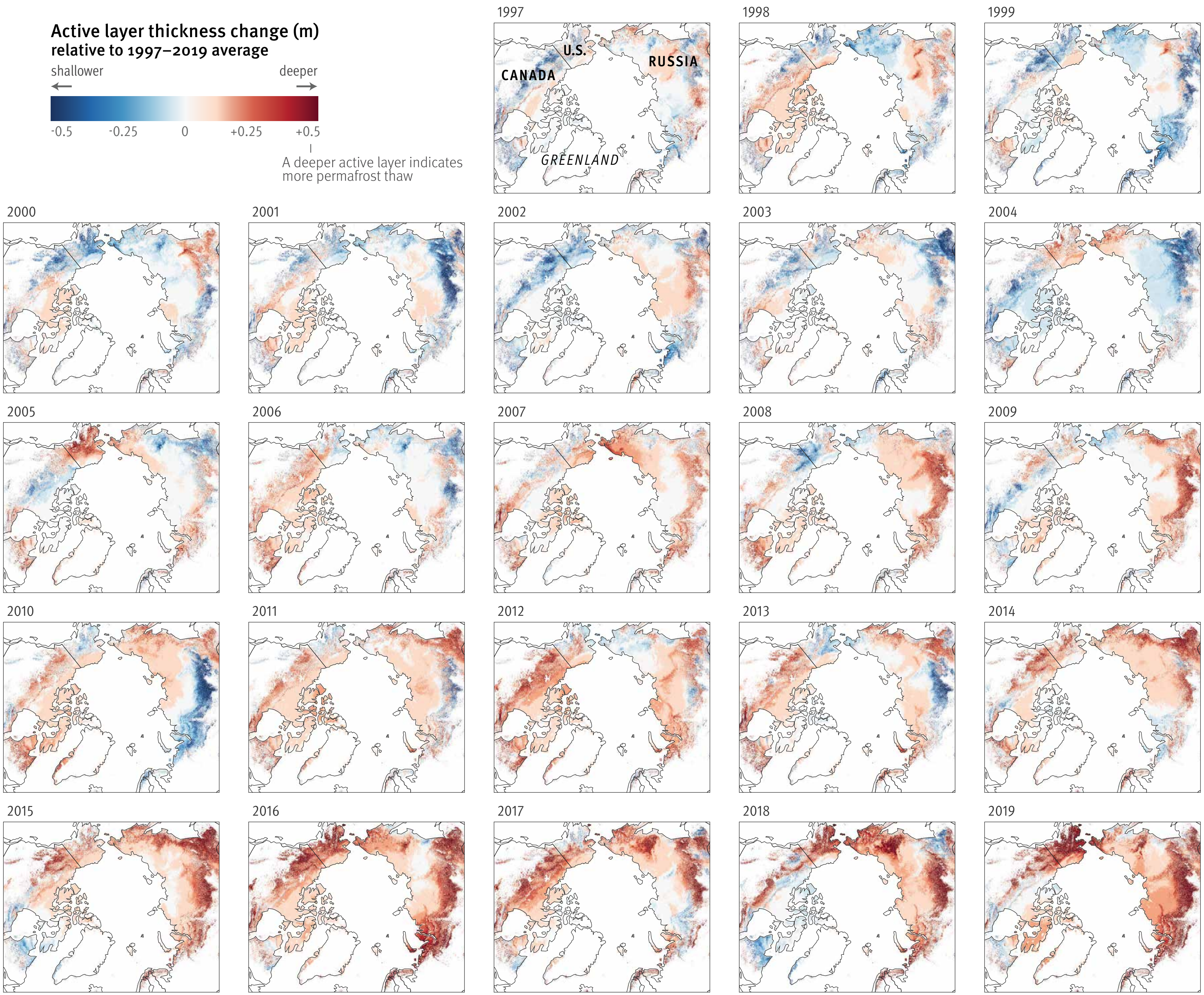
Thickening of the active layer

The active layer is the ground above the permafrost that thaws each summer and refreezes with the return of lower temperatures in autumn. How deep the active layer thaws depends on local conditions, tending to be thinner in the colder high Arctic and thicker in the southern extent of permafrost where temperatures are higher. Seasonal thawing of the active layer is very important to Arctic ecology as this is where important biogeochemical processes take place. Because it is more responsive to short-term climatic variation, the depth of the active layer can vary considerably from year to year. However, long-term trends in active layer thickness are, together with the permafrost temperature itself, an important indicator of change in the thermal state of permafrost.

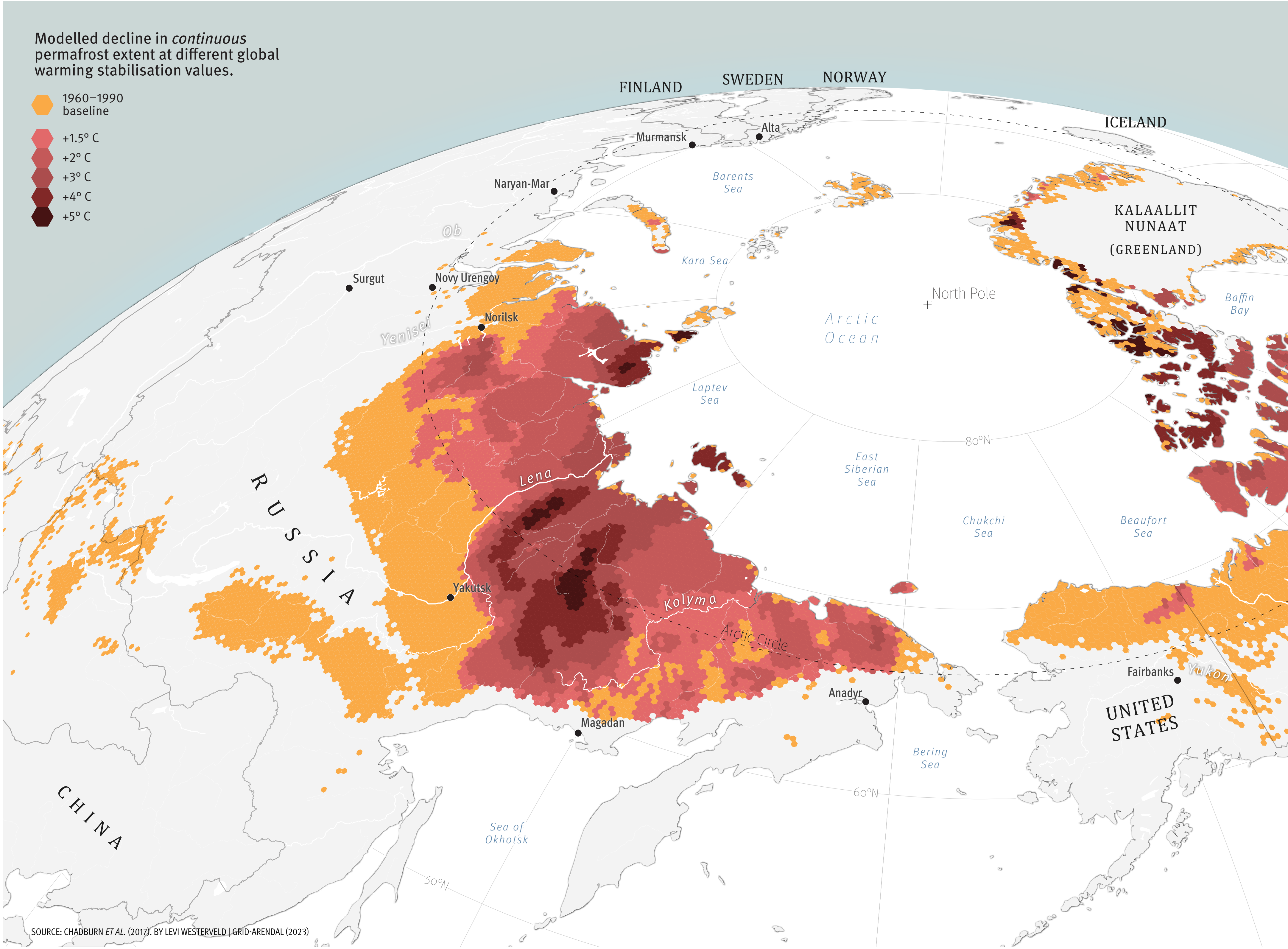
Active layer thickness has been monitored at numerous sites across the Arctic since the 1990s. It is most commonly obtained with an active layer probe, an instrument that can be pushed through the unfrozen sediment until it reaches the frost table. Because it is strongly influenced by seasonal snow cover and air temperatures, it can be more difficult to discern trends in active layer thickness than in permafrost temperature. Where longer data sets are available, observations generally show an increase in active layer thickness.

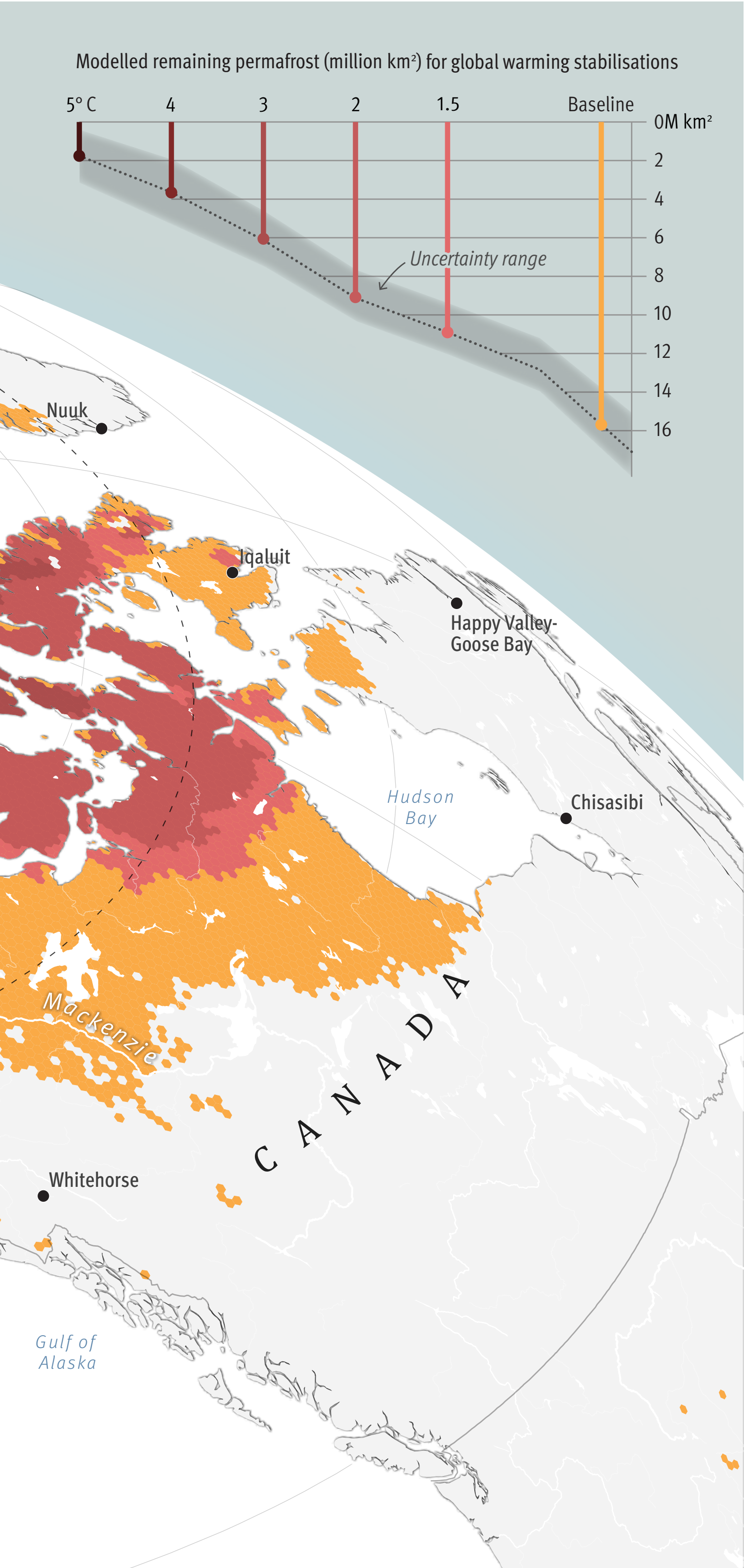
The Circumpolar Active Layer Monitoring network has been monitoring changes in the active layer and near-surface permafrost since 1991. The greatest increases in active layer thickness have been observed in western Siberia and the northern European region of Russia where thickness increased by as much as 0.4 metres between 2009 and 2019. A similar trend has been observed at sites in Scandinavia, Svalbard, and Kalaallit Nunaat (Greenland), although with greater annual variation. The greatest changes in North America were recorded in the Alaskan interior where active layer thickness increased by more than 0.2 metres between 1996 and 2019. Active layer thickness from the Alaska North Slope, through Canada's Mackenzie River valley and into the eastern Canadian Arctic, has experienced both increases and decreases, but current measurements remain similar to those from the 1990s.

Challenges have been identified in assessing trend changes in permafrost using ground temperature and active layer thickness measurements. Active layer thickness is usually measured using the ground surface as a reference point. However, thawing in ice-rich locations may result in ground subsidence and a lowering of the permafrost table, and unless ground surface elevation is also monitored, active layer deepening is underestimated. Results can also be affected by the time of year that measurements are taken, particularly whether they are taken at the time of maximum thaw or not, which itself can vary from year to year.



SOURCE: OBU *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)


Modelled decline in *continuous* permafrost extent at different global warming stabilisation values.
1960–1990 baseline
+1.5° C
+2° C
+3° C
+4° C
+5° C
FINLAND
SWEDEN
NORWAY
ICELAND
KALAALLIT NUNAAT (GREENLAND)
Murmansk
Alta
Naryan-Mar
Barents Sea
Kara Sea
Ob
Surgut
Novy Urengoy
Norilsk
Yenisei
North Pole
Arctic Ocean
Baffin Bay
Laptev Sea
80°N
East Siberian Sea
Chukchi Sea
Beaufort Sea
Lena
RUSSIA
Yakutsk
Kolyma
Arctic Circle
Fairbanks
Yukon
Anadyr
UNITED STATES
Magadan
Bering Sea
60°N
Sea of Okhotsk
CHINA
50°N
SOURCE: CHADBURN *ET AL.* (2017). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



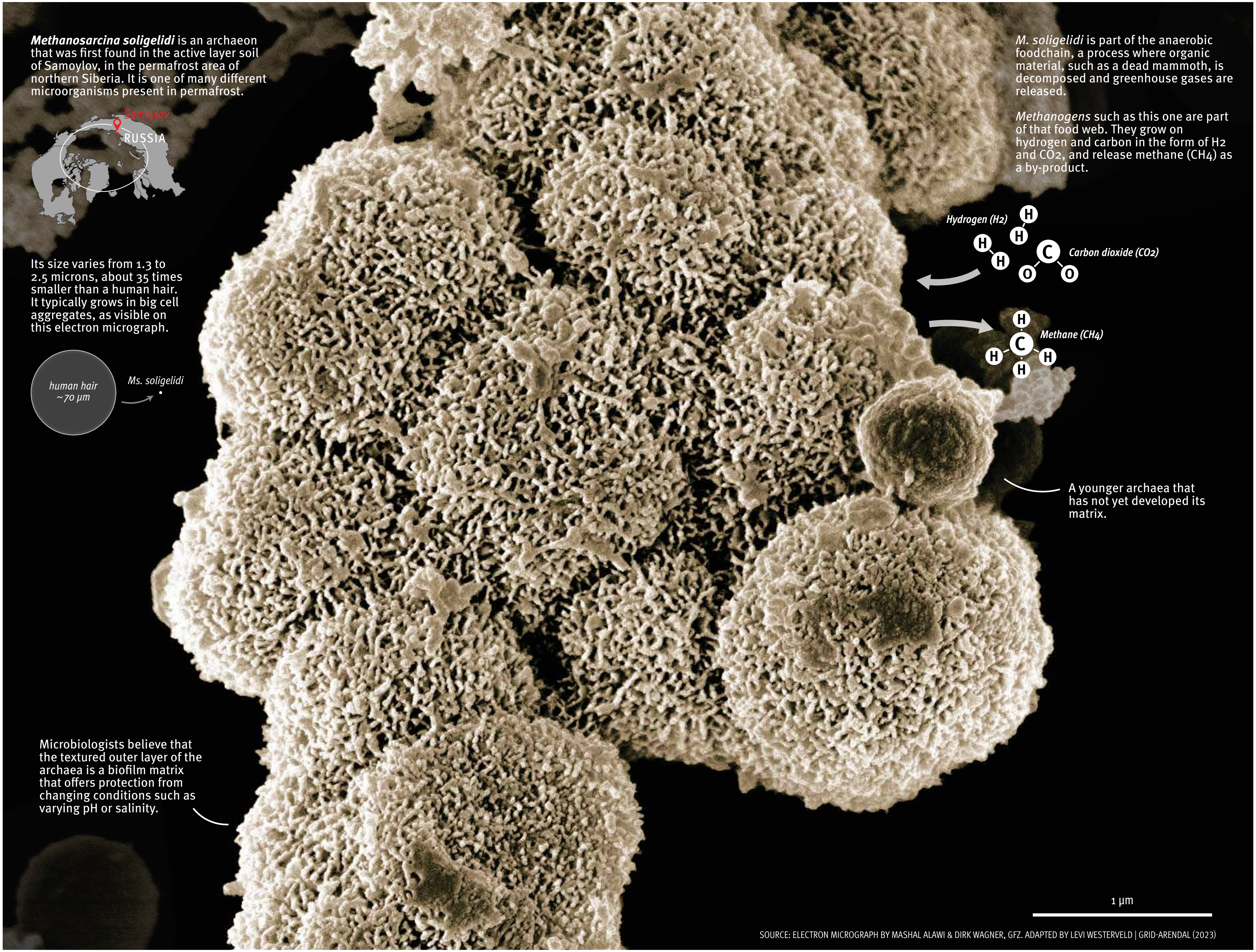
Disappearing act

Declining permafrost extent

Terrestrial permafrost underlies approximately 14 million km² of the exposed land area in the northern hemisphere. When permafrost thaws, it can have significant impacts on terrestrial ecosystems, landscape processes, the hydrological cycle, greenhouse gas emissions, and infrastructure. The sensitivity of permafrost to climate warming and the potential for large-scale environmental changes make it important to understand the full extent of projected permafrost changes. All the latest climate models show continued warming leading to permafrost thaw, but the amount of permafrost that may be lost varies considerably under the different Earth system models due to a lack of data and limitations within the models themselves. Permafrost is generally considered to be lost when the active layer does not refreeze fully in the winter. This means that full thawing of the permafrost, down to hundreds of metres, can take much more time.

One approach for estimating future permafrost loss under different warming scenarios looks at the relationship between mean annual air temperature and permafrost occurrence. One study estimated that if the climate is stabilised at 1.5 °C above pre-industrial levels, between 2.6 and 6.8 million km² (over 30 per cent) of the present-day near-surface permafrost area could be lost. Stabilising the climate at 2 °C above pre-industrial levels would see that loss increase to between 4.4 and 8.6 million km² (over 40 per cent) of permafrost area. If warming increases even more, a large part of the existing near-surface permafrost will thaw. With 5 °C of warming, near-surface permafrost extent will be reduced to 0.3–3.1 million km², and with 6 °C of warming, it could disappear altogether.

The rate of permafrost degradation is not uniform across the Arctic. Permafrost degrades quickest in the western Russian Arctic where mean annual ground temperatures have increased from 0.03 °C to 0.06 °C per year in the continuous permafrost zone and the permafrost table has lowered by as much as 8 metres in the discontinuous zone. Between 1997 and 2018, scientists have observed distinct signs of permafrost degradation in this region: a progressive increase of the active layer thickness, enhanced permafrost degradation after ground ice has melted, and a lowering of the permafrost table.



SOURCE: ELECTRON MICROGRAPH BY MASHAL ALAWI & DIRK WAGNER, GFZ. ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)

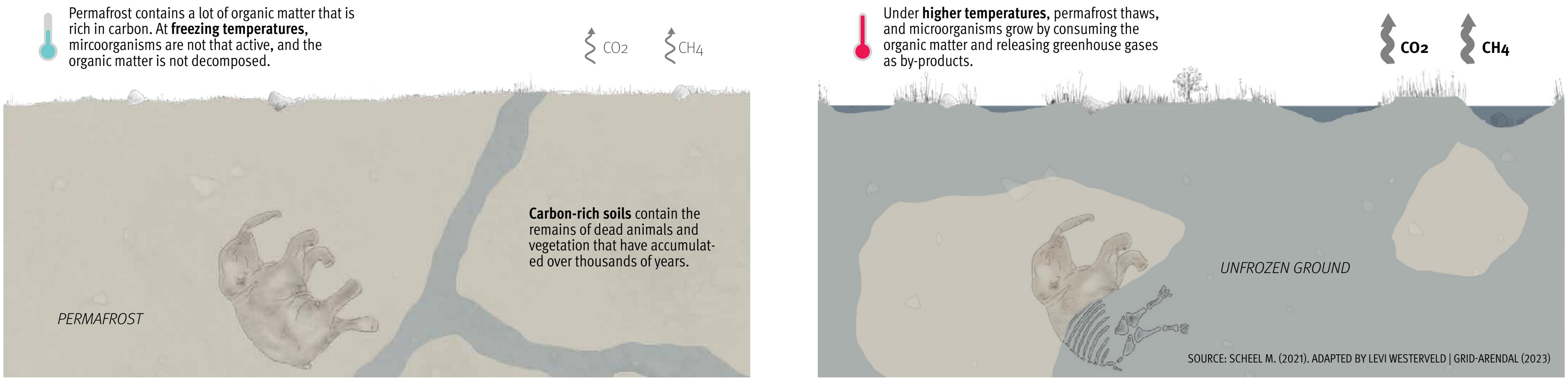
Microorganisms, macro effects

Permafrost carbon cycle

Permafrost contains vast amounts of organic carbon, the carbon found in all living organisms and their remains. The organic carbon in permafrost consists mostly of dead animals and plants that have accumulated and remained frozen for thousands of years. As temperatures increase and permafrost thaws, this organic matter starts to decompose and release carbon dioxide and methane into the atmosphere.

Most of the Earth's carbon is stored in rocks. The rest is found in the atmosphere, soils, oceans, and living organisms, and cycles through these reservoirs in a process known as the global carbon cycle. In the permafrost subcycle, carbon is transferred from the soil to vegetation and microbes, released into the atmosphere, transferred back into vegetation via photosynthesis, and finally returned to the soil where the process starts again. As long as the soil is frozen, microbial decomposition of soil organic matter is drastically slowed down and carbon is able to accumulate. Many microorganisms are able to survive the freezing temperatures either by slowing their metabolism, or by entering a resting state. When permafrost thaws, the frozen water in the soil melts, making the organic matter accessible to soil microbial decomposition. While one group of microorganisms, methanotrophs, are able to consume methane (and are the only known sink of methane), most processes occuring during permafrost thaw increase the release of greenhouse gases into the atmosphere.

The presence or absence of oxygen during decomposition determines whether carbon is released as carbon dioxide or methane. In aerobic soils, where oxygen is available, such as collapsed and drained sites, the decomposition of organic carbon releases more carbon dioxide. In contrast, anaerobic decomposition in oxygen-limited and often waterlogged conditions (e.g., in permafrost thaw lakes) releases both carbon dioxide and methane. Although the thawing of permafrost soils leads to deeper rooting vegetation and more carbon sequestration, this cannot compensate for carbon emissions from these soils while they thaw. Due to the potential vulnerability of large permafrost carbon stores, their degradation is globally important. Converting even a small portion of the permafrost carbon to greenhouse gases could increase the rate of climate change, spurring further permafrost warming and even more greenhouse gas emissions in a positive feedback loop.



SOURCE: SCHEEL M. (2021). ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Faster, deeper, stronger I

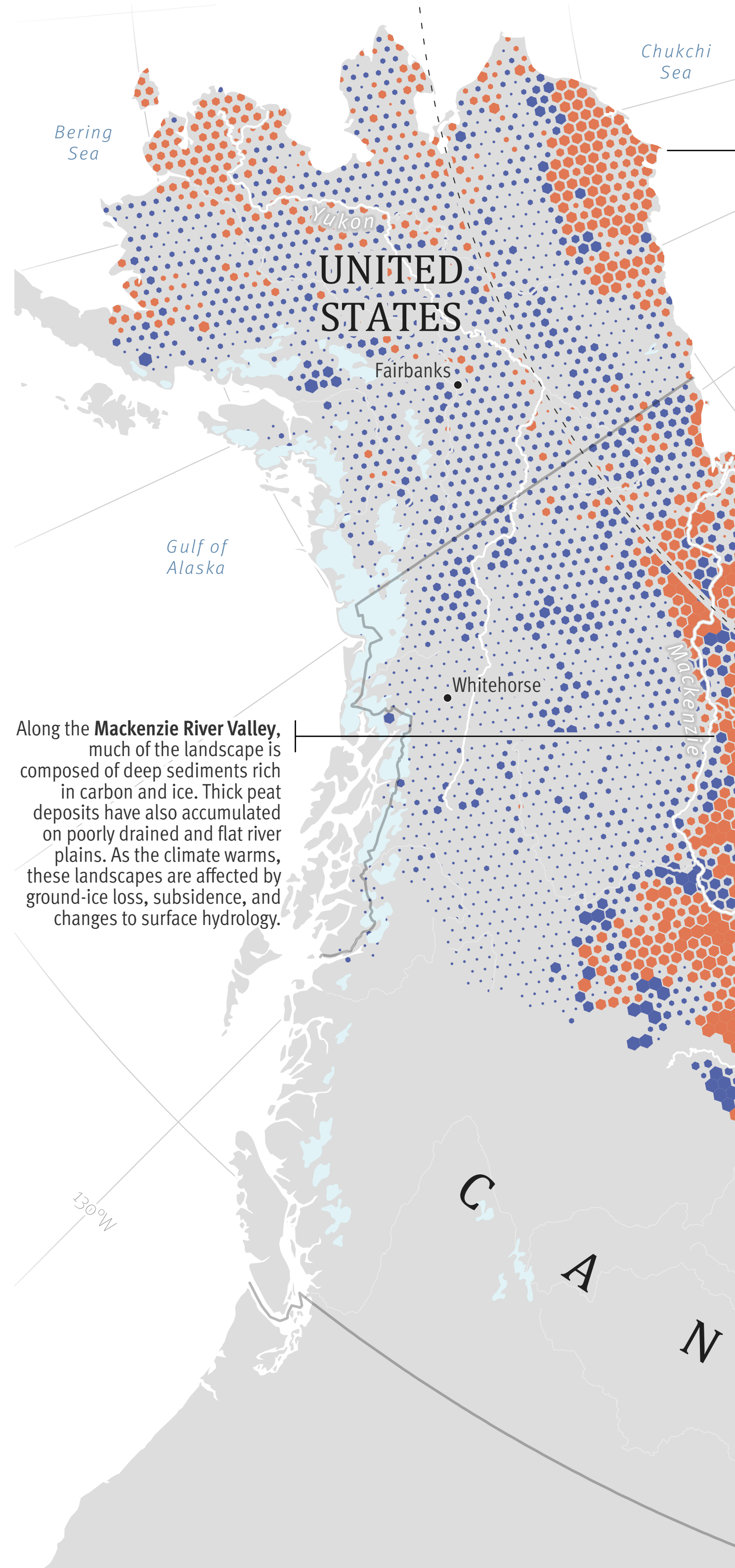
Speed of thaw in North America

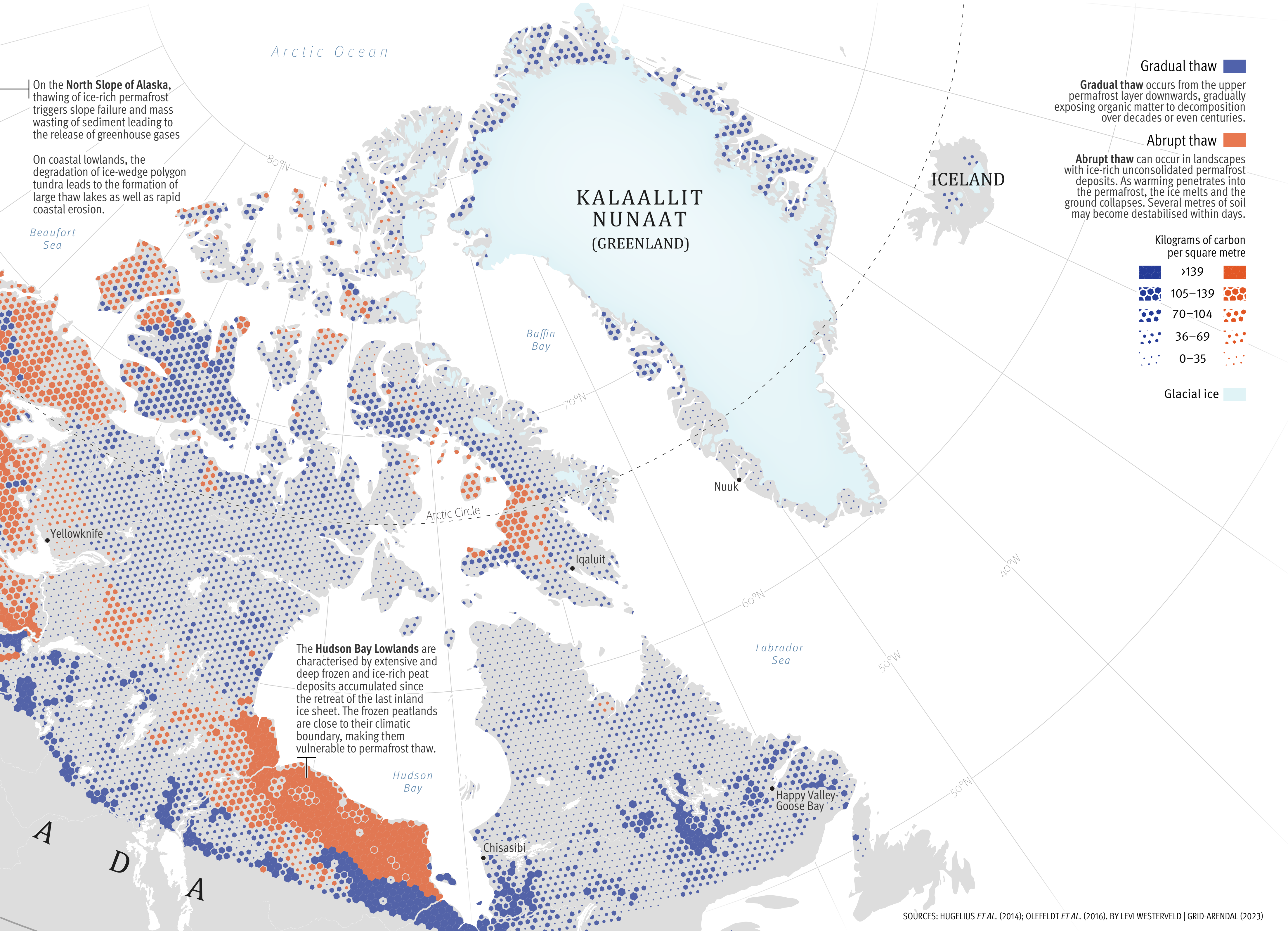
Different types of permafrost landscapes show varying responses to warming. Permafrost thaw is often divided into two main types: gradual thaw and abrupt thaw. Gradual widespread thaw occurs from the upper permafrost layer down into ever deeper layers. This exposes organic matter to decomposition over decades or even centuries. Abrupt thaw occurs where erosion takes place along riverbanks, lake shores, and coasts, and in ground containing large amounts of pure ice. The ice can make up much of the ground volume and also cements the frozen ground together. As warming penetrates the ground, permafrost collapses as the ice melts away. This ground surface collapse (called thermokarst) accelerates the thaw, and instead of thawing centimetres each year, several metres of permafrost can become destabilised within days or weeks. The landscape changes create new lakes, ponds, landslides, and other landforms.

Along the Alaska North Slope and into Canada, in an area that runs from the northern edge of the Brooks Range to the Beaufort Sea, the tundra landscape is rich in both ground ice and organic matter. In the foothills of the Brooks Range mountains and along river valleys, the thaw of ice-rich permafrost triggers slope failures and mass wasting of sediments. This not only leads to greenhouse gas production as frozen organic matter starts to thaw and decompose, but also releases large amounts of sediments and pollutants into aquatic ecosystems. On coastal lowlands, the degradation of ice-wedge polygon tundra leads to the formation of large thaw lakes as well as rapid coastal erosion.

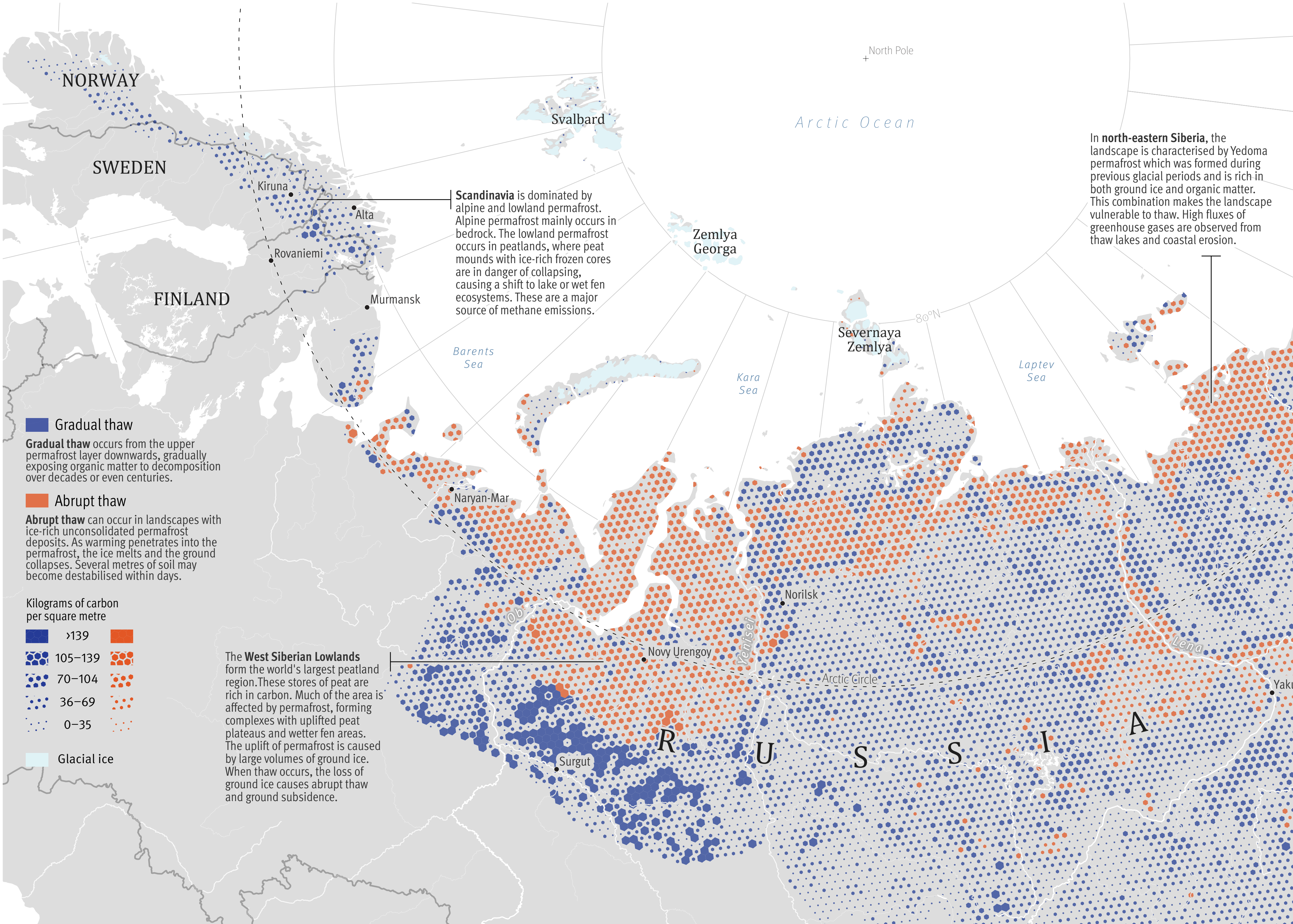
Rapid thawing is also occurring along the Mackenzie River valley in the Northwest Territories (Canada), where much of the landscape is comprised of thick, ice- and carbon-rich sediments. Thick peat deposits have also accumulated on poorly drained and flat terrain. As the climate warms, these landscapes are affected by ground-ice loss, subsidence, and changes to surface hydrology.

The western Hudson Bay Lowlands are characterised by extensive and deep peat deposits which have accumulated since the retreat of the last inland ice sheet. These are the world's second largest peat deposits, after the west Siberian lowlands. Much of the peat accumulated in a slightly warmer climate during the Holocene thermal maximum, but as the climate cooled a few thousand years ago, the active layer became shallower and turned peat across the area into a frozen state. The frozen peatlands are rich in ground ice, and as they are close to the limits of their climate zone, they are vulnerable to permafrost thaw.

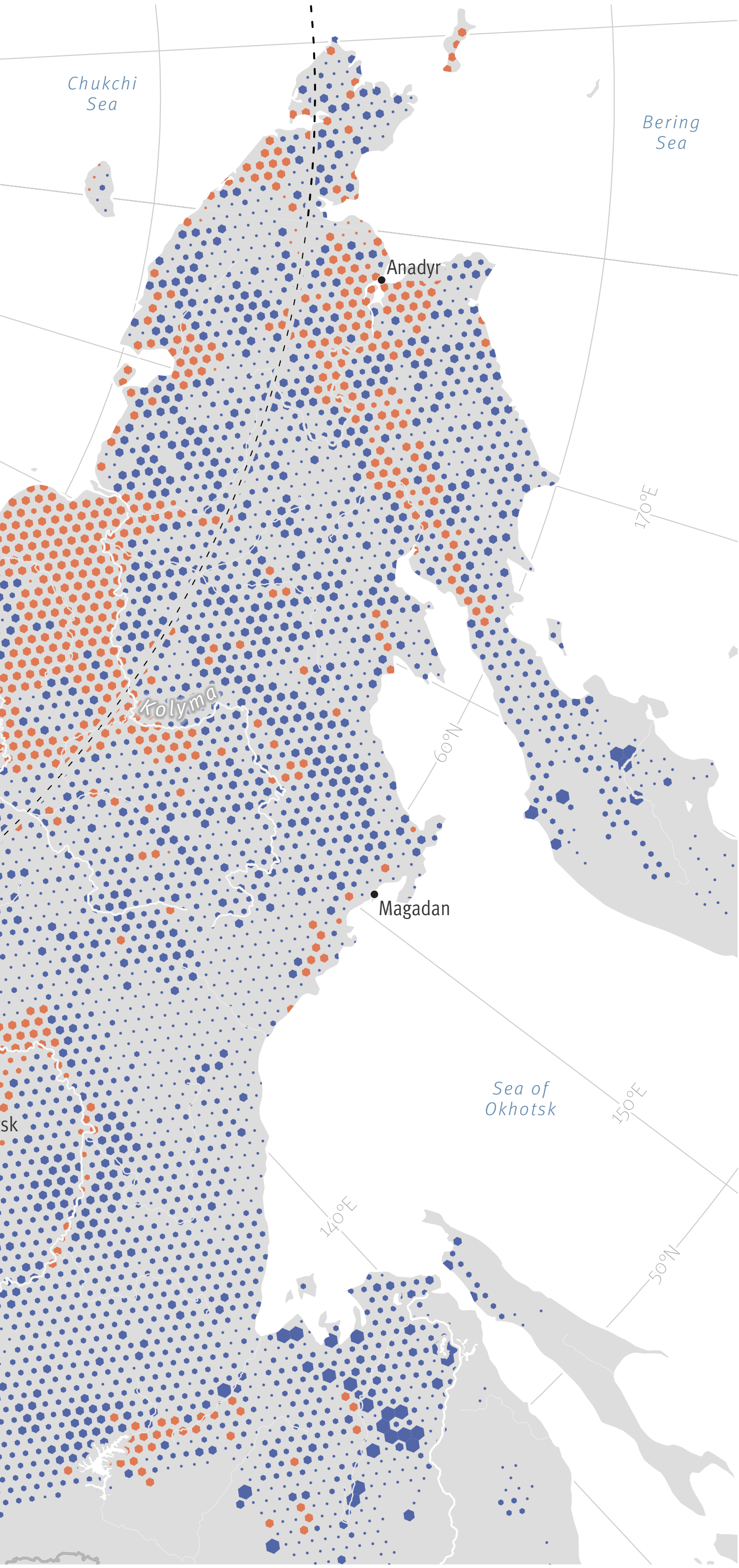




SOURCES: HUGELIUS *ET AL.* (2014); OLEFELDT *ET AL.* (2016). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



SOURCES: HUGELIUS *ET AL.* (2014); OLEFELDT *ET AL.* (2016). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Faster, deeper, stronger II

Speed of thaw in Scandinavia and the Russian Federation

In Scandinavia (excluding Svalbard), permafrost is dominated by two distinct types: mountain permafrost and lowland permafrost. Mountain permafrost occurs mainly in bedrock and does not contain much organic material, meaning that there are limited climate feedbacks. Thaw of mountain permafrost can destabilise the terrain causing rock falls, landslides, or other mass movements. Lowland permafrost occurs in relatively flat terrain where ice-rich peat and other sediments accumulate in ice-wedge polygons as well as in bogs. If permafrost thaws and the ice melts, these landscapes become vulnerable to collapse. This results in a shift to lake or wet fen ecosystems, which are a major source of methane.

Permafrost occurs across almost 65 per cent of Russia. Although relatively limited in the European part of Russia, it is extensive across Siberia. The Western Siberian Lowlands, which started developing 10,000–11,000 years ago, form the world's largest peatland region. Much of the area is affected by permafrost, forming complexes with uplifted peat plateaus and wetter fen areas. The uplift of permafrost is caused by large volumes of ground ice. When thaw occurs, the loss of ground ice causes abrupt thaw and ground subsidence.

The rate of permafrost degradation in the western Russian Arctic is among the highest in the world. In response to increased temperature and precipitation since the mid-1970s, mean annual ground temperature has increased from 0.03 °C to 0.06 °C per year in the continuous zone. Signs of permafrost degradation are evident, including an increase in active layer thickness and a lowering of the permafrost table (up to 8 metres in the discontinuous zone). Permafrost is warming most rapidly in the tundra in western Russia (up to 0.06 °C per year) and most slowly in the northern taiga (up to 0.04 °C per year).

The landscape in north-eastern Siberia is characterised by Yedoma permafrost or ice complex deposits. These thick deposits were formed during previous ice ages and are rich in both ground ice and organic matter. Massive ice wedges make up much of the ground volume (often more than 50 per cent and up to 90 per cent) and the frozen soil around the ice is high in carbon. This combination of ice and carbon content makes the landscape extremely vulnerable to thaw, and high emissions of greenhouse gases have been measured from thaw lakes and eroding coastal permafrost.

Crossing the threshold

Future scenarios of carbon release

Earth system models are tools used to quantify the response of the Earth's climate system to greenhouse gas emissions. The models also provide a "budget" of how much carbon can be emitted into the atmosphere before a particular warming threshold is crossed. Understanding how the Earth's climate will change under different scenarios (or emission levels) is vital to setting greenhouse gas emission targets to limit the global temperature increase to 1.5 °C, as recommended in the Paris Agreement.

The Earth's climate system is too complex to make projections with a high degree of certainty. Earth system models do not include all sources of carbon released to the atmosphere, and calculating the emissions from natural sources, such as terrestrial permafrost, has a much higher degree of uncertainty than from anthropogenic sources, such as industrial activity. As a result, IPCC did not include emissions from permafrost until its Sixth Assessment Report. Contributions from subsea permafrost are even more difficult to model due to the lack of critical data.

Net carbon flux is the difference between the carbon taken up by plants through photosynthesis and the carbon released into the atmosphere from sources such as respiration and land-use change. As permafrost thaws, more stored carbon becomes available for release into the atmosphere. Although there will also be greater carbon uptake by plants as the climate warms, modelling shows that more carbon will be released than can be used in primary production. The greatest carbon emissions are expected to occur under Representative Concentration Pathway 8.5, the highest emissions scenario up to 2100. An intermediate emissions scenario, however, leads to little change in net emissions as the increased emissions from permafrost thaw is compensated by an increase in uptake by vegetation.

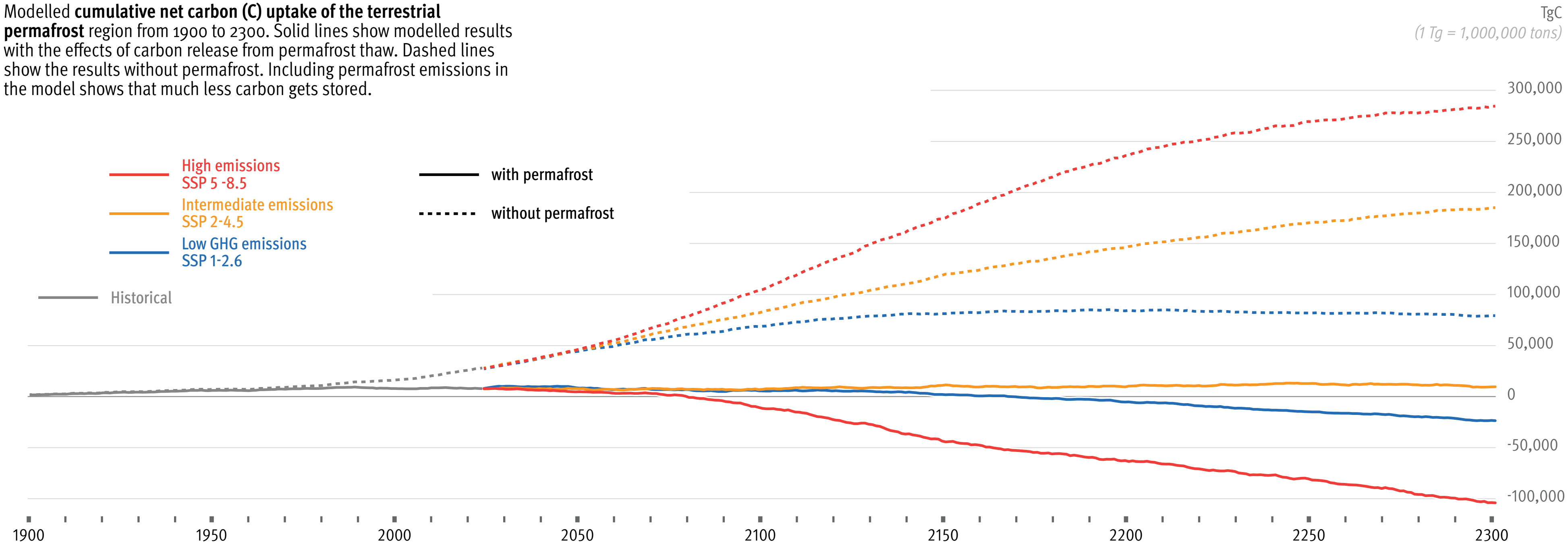
According to the IPCC Sixth Assessment Report, for every degree of global warming, anywhere between 3.1 and 41 billion tons of carbon dioxide will be emitted from terrestrial permafrost by the year 2100. Although a great deal of uncertainty surrounds the scale of emissions, it is agreed that as more atmospheric warming occurs, more carbon will be emitted from thawing permafrost, contributing to even more global warming. Missing from these estimates are emissions from the abrupt thaw of permafrost, something which scientists are only just beginning to understand. Some estimates suggest that for every degree of warming, abrupt thaw will release almost twice as many emissions as from gradual thaw.

In current models, subsea permafrost thaw is similar across the different climate scenarios. Up to around the year 2100, all scenarios show permafrost thawing at about four times the rate prior to anthropogenic climate warming. After 2100, the loss of subsea permafrost continues at relatively similar rates. In the high emission scenario, however, subsea permafrost starts to thaw dramatically, about 15 to 18 times faster than before anthropogenic climate warming. The rapid thaw of subsea permafrost is tied to the loss of Arctic sea ice, which will cause the seabed on the Arctic shelves to warm up faster thus accelerating permafrost thaw. The continued reduction of sea ice is very likely, even under optimistic carbon emission reduction scenarios. Since the development of sea ice drives the formation of cold brine, which cools the seabed, the long-term effect of sea ice reduction will be warming of the permafrost below the shallow Arctic shelf areas.

Based on the limited knowledge of the quantity and quality of organic matter in subsea permafrost, models suggest that at the current rate of climate warming, methane-producing microbes will decompose more than 400 million tons of carbon annually after the year 2100. Most of this carbon decomposition produces methane below the sea floor, over 200 million tons per year under the high emission scenario. However, it is difficult to predict how much methane will ultimately reach the atmosphere. In the sediments and water column above the thawing permafrost, methanotrophic microbes can oxidise the upward-migrating methane under both aerobic and anaerobic conditions, turning it into carbon dioxide before it reaches the sea floor and the atmosphere. The benthic methane sink is an extremely efficient microbial filter for upward-migrating methane and usually consumes a huge fraction of the methane flux. The current estimated global total of methane emissions from the ocean to the atmosphere is approximately 4–10 million tons per year. Even under the most extreme climate change scenarios, the maximum amount of methane released from thawing subsea permafrost, would only be about double what they are today.

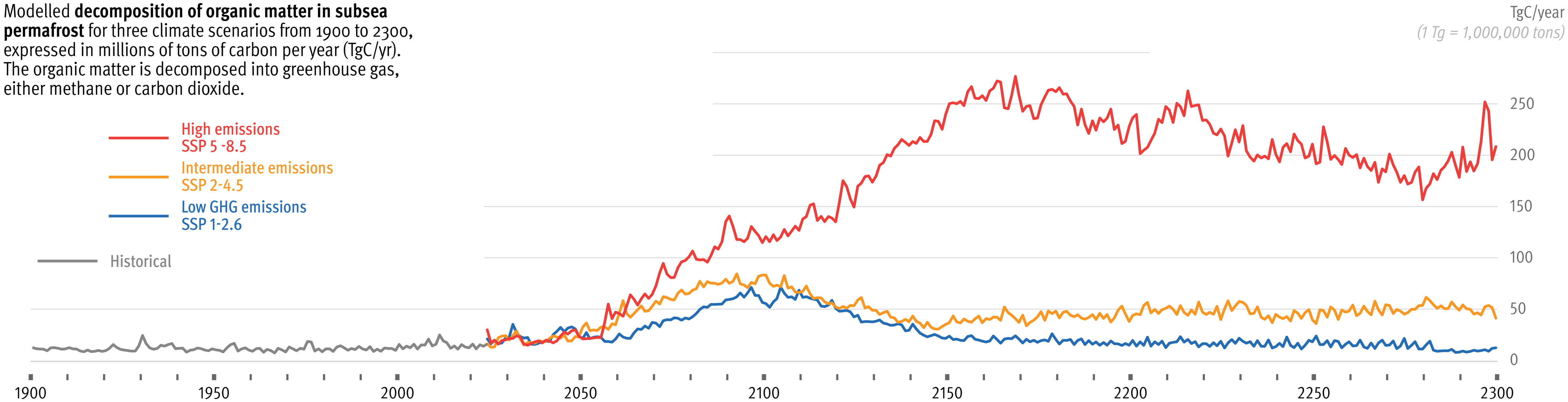
Even if society reaches its carbon emission targets, emissions from permafrost may persist, which in turn could lead to overshooting those same targets. As permafrost thaws, it adds more greenhouse gases to the atmosphere, which drives further warming and risks exceeding warming predictions. In this scenario, permafrost carbon would be irreversibly lost because most types of permafrost do not recover quickly or easily. Therefore, permafrost thaw could also trigger a carbon loss that continues for centuries. These future emissions from permafrost need to be accounted for in modelling.

Modelled **cumulative net carbon (C) uptake of the terrestrial permafrost** region from 1900 to 2300. Solid lines show modelled results with the effects of carbon release from permafrost thaw. Dashed lines show the results without permafrost. Including permafrost emissions in the model shows that much less carbon gets stored.

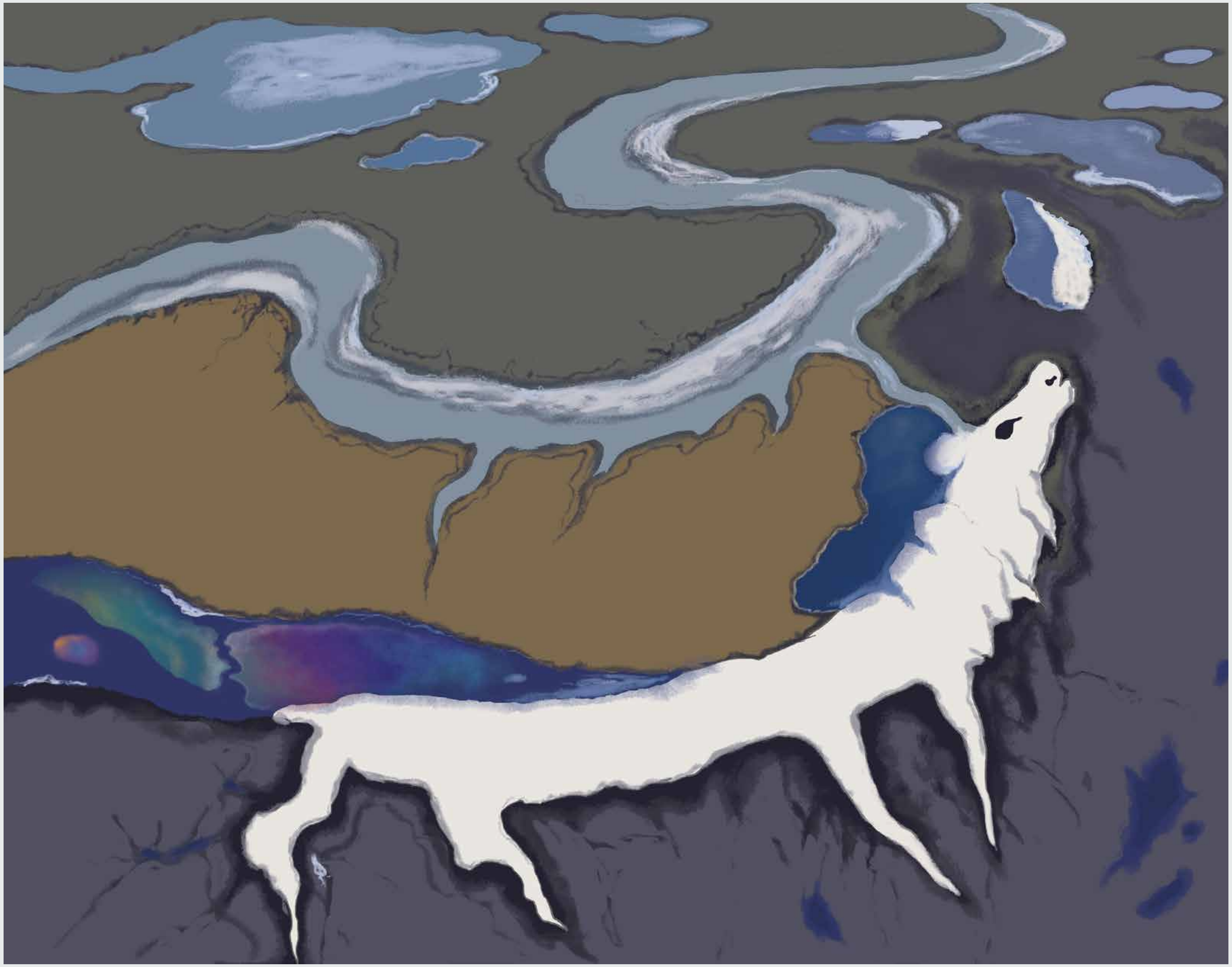


SOURCE: KLEINEN AND BROVKIN (2018). ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Modelled **decomposition of organic matter in subsea permafrost** for three climate scenarios from 1900 to 2300, expressed in millions of tons of carbon per year (TgC/yr). The organic matter is decomposed into greenhouse gas, either methane or carbon dioxide.



SOURCE: RIDOLFI, ARNDT *ET AL* (IN PREP). ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)



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Dmitry Streletskiy

I grew up in Moscow right next to a park, where I mostly spent my childhood outside climbing trees. Moscow winters were brutally cold with plentiful snow, so I did a lot of skiing and other activities related to cold climates. I think that was part of why I started to be interested in cold climate regions. The Arctic environment, especially the tundra, fascinated me with its low sky and pastel colours.

I've always enjoyed travelling. In high school, I realised that if you did geography, you could get paid to travel. That was my idea of a geographer and that's why I wanted to become one. These days, admittedly, I spend most of my time sitting in the office, but my favourite aspect of work is still being out in the field.

When I was a student, I was part of expeditions that focused on glaciers. To be honest, drilling in glaciers was a little bit too much for me. Permafrost research was more user-friendly since a lot of investigations are constrained by logistics and access to infrastructure. The research happens closer to people and doesn't involve sitting on glaciers in the middle of nowhere at high elevations. Permafrost research is also related to a lot of different job opportunities. You can do all sorts of things.

I realised that permafrost is essential for the people and communities living on it. I started looking at the connection between infrastructure and nature, and what the impacts will be once permafrost starts changing. After completing a PhD in climatology at the University of Delaware, I left for George Washington University, where I have been for more than 10 years researching and teaching classes in Arctic physical geography, natural hazards, and climate change.

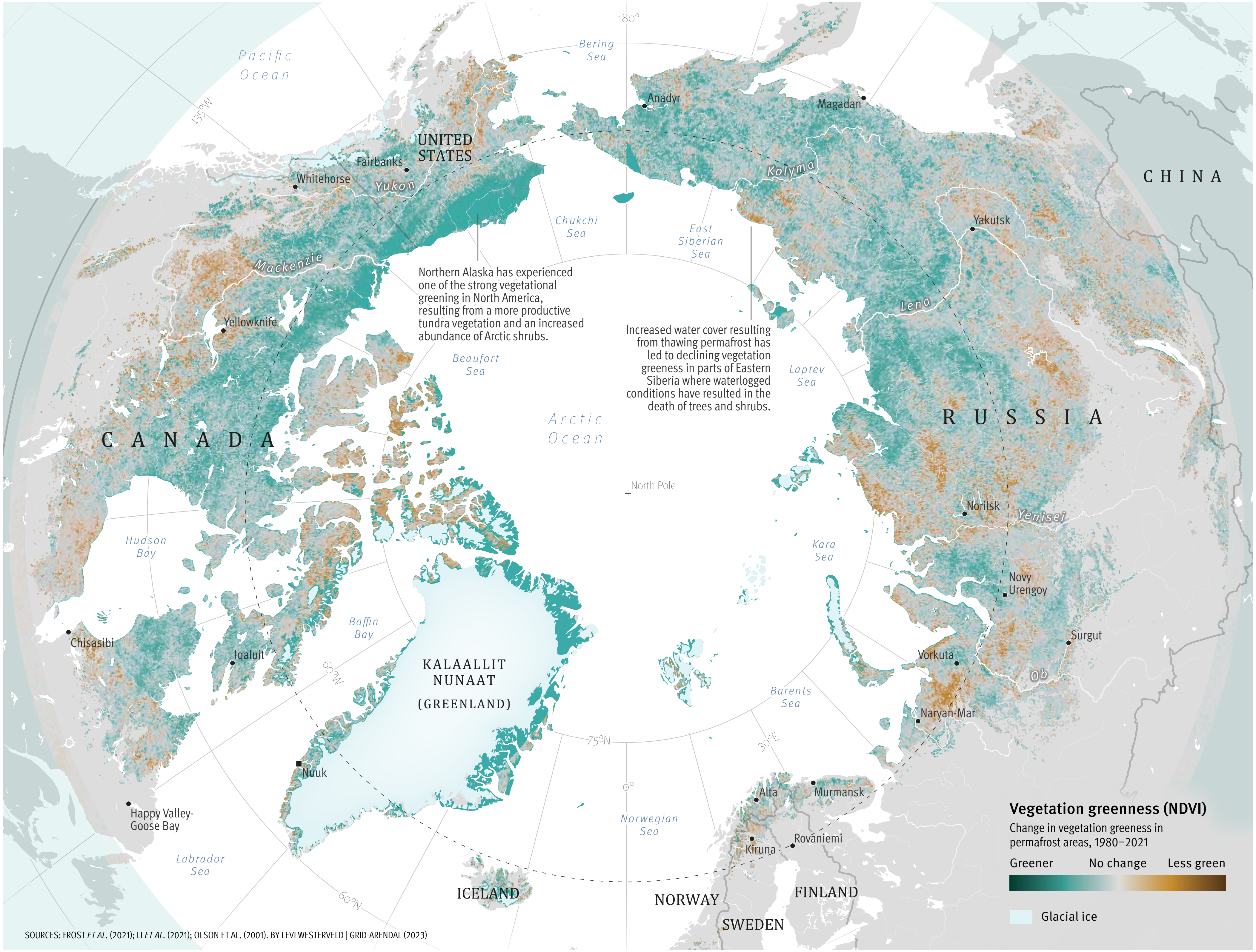
Lecturing students really keeps me motivated because they realise the problems we face, and they are anxious. They really want to do something about it and try to be involved. This helps keep my interest in the topic of permafrost. I think permafrost is an understudied topic and there is no shortage of new permafrost topics to research. We need geographers, biologists, social scientists, economists, engineers, material scientists – you name it.

Some of the things we permafrost scientists communicate do materialise and become policies, and I see some efforts going in the right direction. But sometimes it can get a bit frustrating when you have a good knowledge and understanding of something, but it doesn't necessarily ring a bell with others. I find myself knocking on a door, but there is no one to open it. I think permafrost doesn't get as much attention because it's not like an earthquake or a volcanic eruption with a sudden big event – it's gradual. But then an event like the oil spill in Norilsk happened, and that was like an earthquake. Suddenly I was getting calls and emails from all sorts of people: from municipalities, officers in the government, investors that sit somewhere in Australia or in London. Everyone suddenly wanted to know what permafrost is and what is happening to it.

It's very exciting to be part of a small community and to do something that not many people are doing. I'm at the forefront of a topic, asking new questions and trying to answer them, and then trying to communicate those answers to various groups. I also think it is very exciting to meet various stakeholders, not just scientists at conferences. Talking with these people helps me get a better sense of what's happening on the ground, and I love that.

Moving Grounds

Permafrost Changes



SOURCES: FROST *ET AL.* (2021); LI *ET AL.* (2021); OLSON ET AL. (2001). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Frost and flora

The role of vegetation in permafrost landscapes

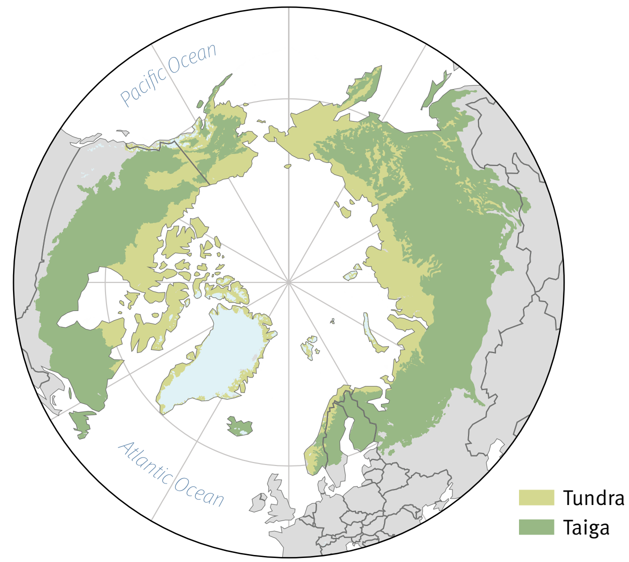
Vegetation plays an important and complex role in permafrost processes. The seasonal thawing of the active layer provides a medium in which plants can grow. In turn, the presence of vegetation helps insulate permafrost, retain moisture in the surface soil, and moderate the effects of changes in air temperature. The influence of vegetation on permafrost is also closely linked with snow accumulation.

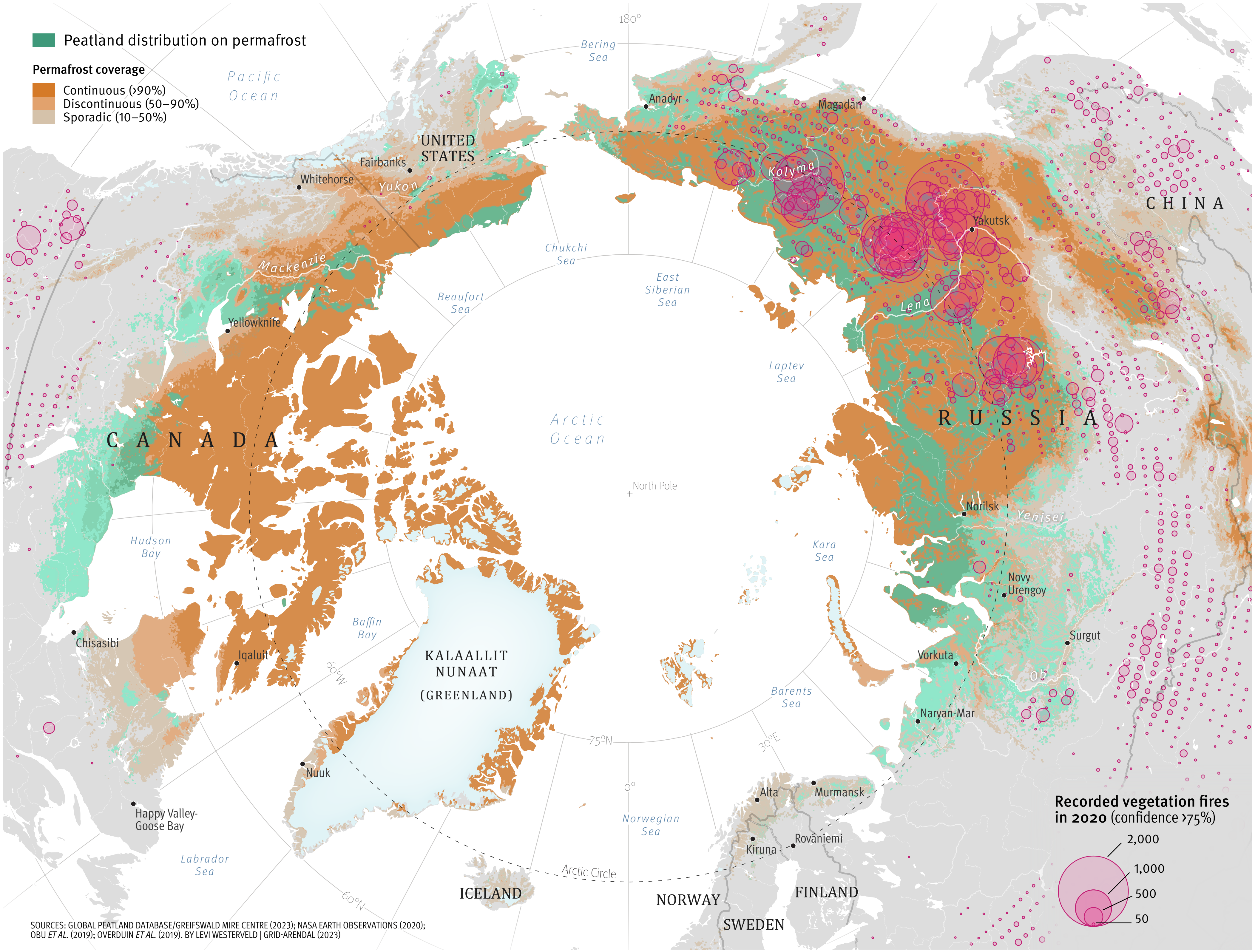
Where vegetation is thick, the shade it provides can cool the soil surface. Dense tree canopies contribute further to cooling by limiting the amount of snow reaching the ground. This affects the distribution of permafrost in the discontinuous zone. Conversely, where the canopy is more open, snow accumulates more readily, providing insulation from cold air temperatures, such as along the treeline. Areas with thick layers of organic matter also offer more insulation from changing air temperatures.

The Arctic tundra is dominated by low-growing vegetation such as grasses, sedges, rushes, small flowering plants, mosses, lichens, and shrubs. However, the warming of the Arctic is rapidly changing Arctic vegetation, spreading shrubs further north. Shrubs are more effective in trapping snow than low-growing tundra vegetation, mitigating the impacts of air temperature on permafrost. As such, areas with taller shrubs tend to have warmer surface temperatures than those with low-growing tundra vegetation.

Some changes in vegetation are related to permafrost thaw, in addition to warmer and longer summers, increased precipitation, and increasing atmospheric carbon dioxide concentrations. Gradual permafrost thaw may stimulate vegetation growth through the release of nutrients as soil carbon decomposes. But when thaw is abrupt, plant communities may experience high mortality and changes in composition as the soil surface subsides or collapses. As permafrost thaws, changes also occur in the thickness of the active layer, local topography, and soil moisture content. The relationship between the change in tundra vegetation and permafrost, however, is still not well understood.

As Arctic summers become warmer and precipitation patterns change, climate-related disruptions such as extreme weather and vegetation fires are also becoming more common and are expected to increase in the coming decades. More frequent hot summers sometimes allow fires to continue smouldering over the winter and then flare up again in the subsequent spring. The loss of vegetation and the insulating surface organic layer to fire can exacerbate permafrost warming. Studies have found the mean annual ground surface temperature is 1-7 °C higher at sites that have burned.





SOURCES: GLOBAL PEATLAND DATABASE/GREIFSWALD MIRE CENTRE (2023); NASA EARTH OBSERVATIONS (2020); OBU *ET AL.* (2019); OVERDUIN *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Fire on Ice

Peat, permafrost, and fire

Large areas of Arctic permafrost are covered by peatlands: wetland ecosystems that have a layer of partially decomposed organic matter (peat) at the surface. They are most widespread in the southern Arctic, especially in Canada's Hudson Bay lowlands and the Mackenzie River Valley as well as across Siberia, becoming less common further north where lower precipitation, low temperatures, and short growing seasons limit their formation. Peatlands play a crucial role in regulating the Earth's climate, absorbing and storing carbon dioxide from the atmosphere, helping to mitigate the effects of global warming.

Of the estimated 5 million km^2 of peatlands globally, most are in the subarctic and boreal zones. Northern peatlands cover close to 4 million km^2, almost half of which – about 1.7 million km^2 – are underlain by permafrost. Peatlands are significant carbon storehouses, containing almost one-third of the world's soil carbon, an estimated 450 to 650 billion tons. Most of this carbon, 415 billion tons, is stored in northern peatlands.

Peatlands play an important role in maintaining permafrost with the thick peat layer helping to protect it from temperature variations. In summer when peat is dry, it insulates the underlying permafrost from warm air. When peat is wet or frozen, it allows cold air to penetrate the soil, thus helping conserve permafrost where it might not otherwise exist. However, changes in temperature and precipitation are leading to a decrease in the extent of permafrost peatlands. The area of permafrost peatlands has already decreased from an estimated 2 million km^2 in pre-industrial times to 1.7 million km^2 today. It is projected that, under 2 °C of global warming, this area will decrease to 1 million km^2, and at 6 °C of warming, it is thought that almost all permafrost in these peatlands will have disappeared.

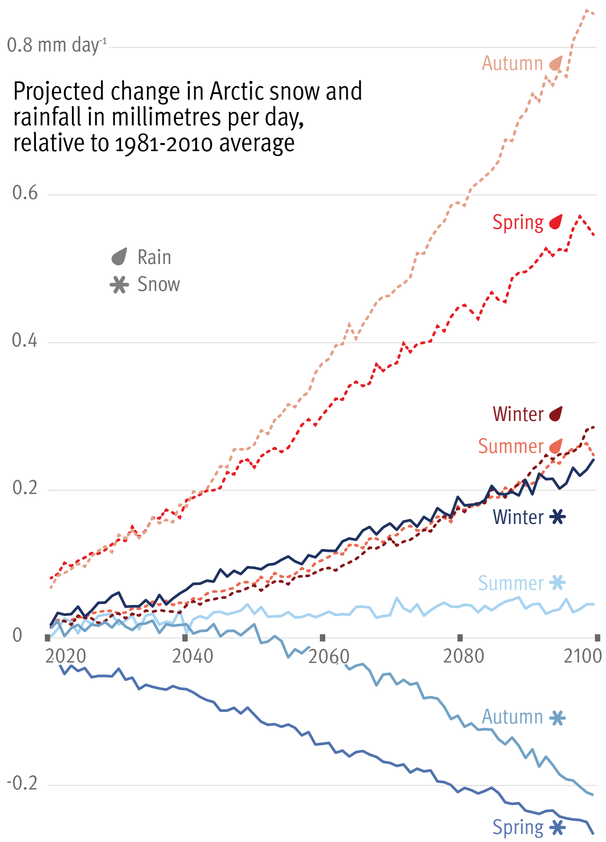
Peatlands in high northern latitudes, including permafrost peatlands, are vulnerable to changes in temperature and precipitation. As temperatures increase, it can dry out the overlying peat, making it more susceptible to fires. Not only do fires release vast amounts of carbon from the burning peat but they also destroy the insulating layers of vegetation, peat, and soil, increasing the rate of permafrost thaw. The combined effects of climate change and wildfires can turn permafrost peatlands from carbon sinks to carbon sources creating a positive feedback loop that exacerbates the effects of global warming. The impacts to permafrost are even more severe in the discontinuous zone.

Climate change is increasing the risk of catastrophic wildfire events in many regions of the world; even the Arctic is no exceptions. The summers of 2019 and 2020 saw unprecedented wildfires in the Arctic, the worst occurring in Siberia, an area with extensive permafrost peatlands. Higher winter and spring temperatures led to fires occurring as early as May and burning for longer periods of time, and further north than usual. In peat deposits, fires can also continue to smoulder undetected beneath the surface, bursting back into life weeks or even months later when the conditions are favourable. Almost 140,000 km^2 burned in the 2020 Siberian fires, most occurring in the permafrost zones. It is estimated that the fires in these carbon-rich peatlands released 244 million tons of carbon dioxide, 35 per cent more than the previous record set in the 2019 fires.

State of matter

Water, snow, and permafrost

Whether as precipitation, in waterbodies, or as ice in the ground, water influences the state of permafrost, how quickly it thaws, and with what consequences. Snow, for example, can have either a cooling or a warming effect on the underlying permafrost depending on snow depth as well as timing of accumulation and duration over the cold season. Where snow is thicker, the ground surface temperature is also higher because cold winter air cannot fully penetrate into the ground to cool it down. Periods of permafrost warming in Alaska (late 1980s to early 1990s) and Norway (1999–2009), for example, have been linked to deeper snow cover as well as increased air temperature. A thin snow cover cools the ground due to the high albedo, which leads to reflection of long wave radiation from the white snow surface.



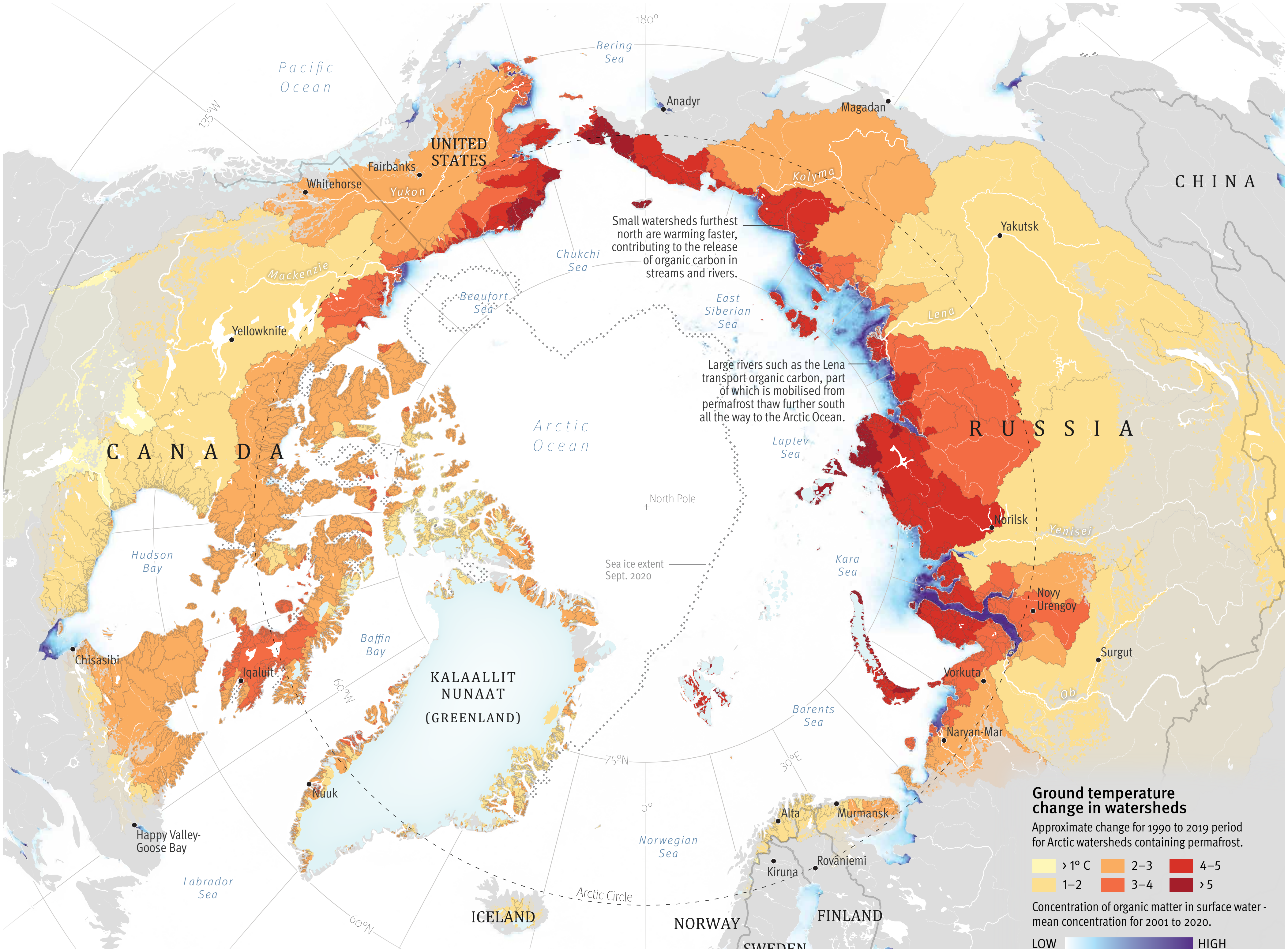
SOURCE: MCCRYSTALL *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

The timing of snow accumulation and melt is also important. When winter snow arrives late, the active layer may refreeze and the permafrost below may cool more quickly in response to decreasing air temperature, whereas earlier snow accumulation may delay these processes. In the spring, the effect is reversed: an earlier melt may lead to earlier thawing of the active layer, while thawing is delayed in areas where snow cover lingers longer. Snow-covered ground cannot thaw. The active layer can only start developing once the snow has melted.

All climate change scenarios indicate longer and wetter summers in the Arctic, with higher precipitation under the high emissions scenarios. Greater summer rainfall can lead to increased permafrost thaw because of the high heat capacity of water. After very wet summers, thaw depths may take longer to return to "normal" values. Higher rainfalls have an even greater effect in disturbed areas, for example, where the ground has subsided due to permafrost thaw. Surface water ponding is not unusual in these sites and may lead to further thawing. Increasing rainfall may also lead to increasing active layer depth in wetlands. Although the vegetation provides some protection, water tends to accumulate in these low-lying areas and, as it warms, can heat the permafrost beneath it.

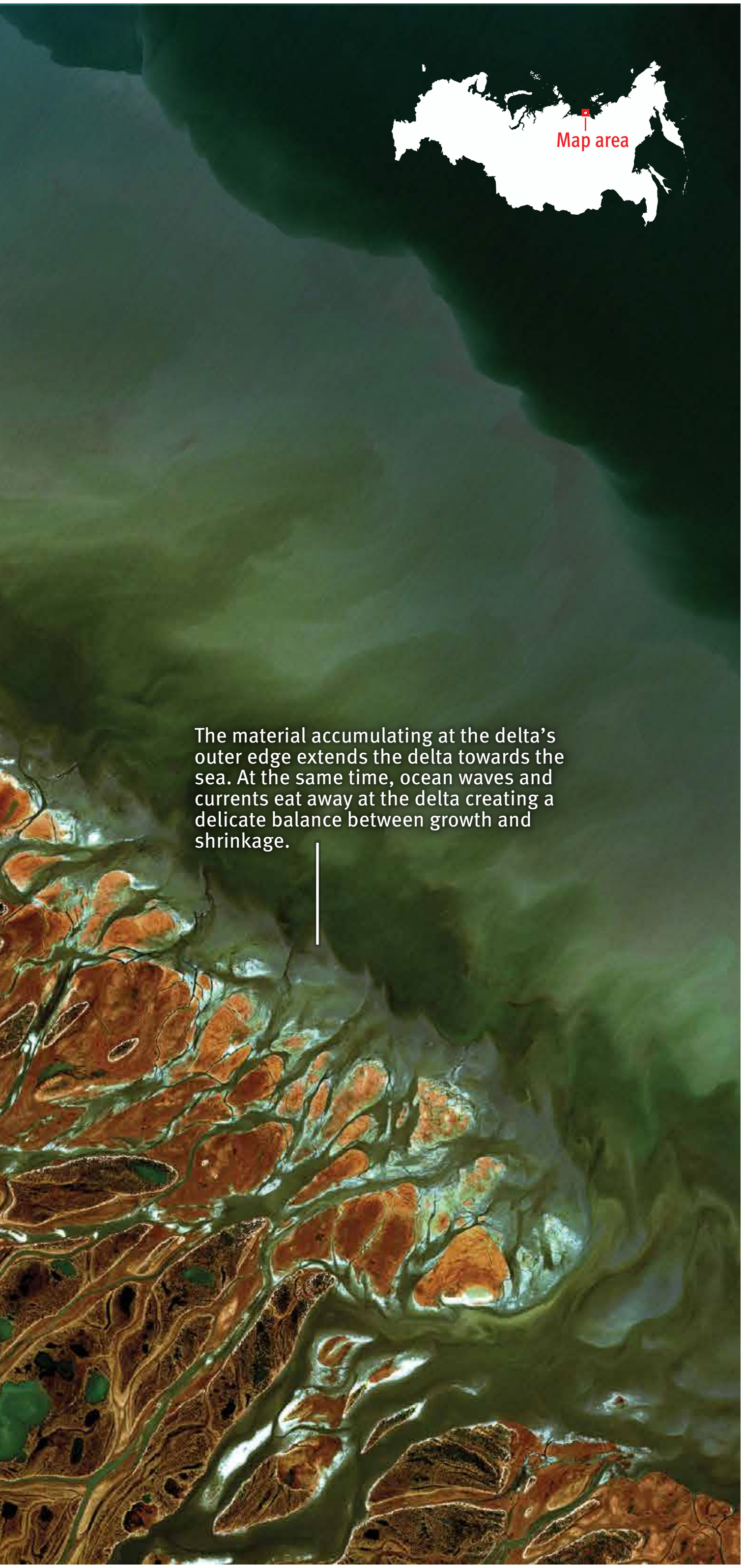
Permafrost has a big impact on the hydrological functioning of the soil, which in turn impacts Arctic hydrology in general. Earlier snowmelt and increased river flows in the Arctic are leading to earlier and longer periods of inundation in floodplains resulting in greater warming of the underlying permafrost. Later freeze-up of rivers in permafrost-dominated catchments means that more and warmer water runs through permafrost terrain later into fall, which can also lead to a later build-up of sea ice along the Arctic coasts.

Thaw-induced changes affect all Arctic rivers, but smaller river systems are warming the fastest. The northernmost permafrost regions have thousands of small river reaches or segments, most of which are underlain by continuous permafrost and soils with high carbon content. In many areas, the landscape is strongly influenced by ice within the permafrost. Ice-wedge polygon terrain is an important example of this. In flat coastal systems, these ice-wedge polygons serve as small water retention basins. Warming will cause the ridges around the polygon to thaw and the ice wedges to melt, which will invert the system. This will lead to more efficient draining of the landscape and further thaw. This may, in turn, result in greater leaching and export of nutrients such as carbonate, nitrogen, and phosphorus into rivers, and the Arctic Ocean, and carbon into the atmosphere.



SOURCES: SATHYENDRANATH *ET AL.* (2019); SPEETJENS *ET AL.* (2023). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

SOURCE: SATELLITE IMAGE OF A PART OF THE LENA RIVER DELTA IN NORTH-EASTERN SIBERIA, RUSSIA. COPERNICUS SENTINEL-2, 2020-09-10. LEVI WESTERVELD | GRID-ARENDAL (2023)



The material accumulating at the delta's outer edge extends the delta towards the sea. At the same time, ocean waves and currents eat away at the delta creating a delicate balance between growth and shrinkage.

The rivers run through it

Arctic rivers, deltas and hydrology

Rivers and river deltas play a vital role in Arctic ecosystems. While the Arctic Ocean accounts for about 1 per cent of the Earth's ocean volume, it receives more than 10 per cent of all global river discharge. In addition to its numerous small river systems, the Arctic is home to some of the world's longest rivers, including the Yenisei, Ob, and Kolyma, and three of the world's largest river deltas: the Lena, Mackenzie, and Yukon.

River deltas are fan-shaped landforms created by the deposition of sediment at the mouth of a river. Typically featuring shallow, interconnected channels, lakes, and wetlands, deltas support diverse ecosystems, flora, and fauna, including migratory bird populations. Deltas form a crucial link between the land and the ocean and influence the transport of fresh water, sediments, carbon, and other materials.

Permafrost underlies a substantial part of the catchment of all Arctic rivers, both big and small. The presence of permafrost largely controls the hydrology of the area by restricting the flow of water. The presence of ice in deltas and riverbanks affects erosion and sedimentation processes, as well as the seasonal flow of water into the Arctic Ocean. Frozen riverbanks hinder the transport of sediments because ice protects the ground from erosion. With increased permafrost thaw, the terrain may become unstable and lead to the erosion of riverbanks and formation of thermokarst lakes. In northwestern Canada, for example, increasing temperatures triggered riverbank erosion and an acceleration of retrogressive thaw slumps in the Mackenzie Delta, leading to rapid remobilisation of large masses of sediment and carbon from ice-rich permafrost terrain into adjacent rivers.

As permafrost thaw intensifies, it will become a greater source of organic carbon to the ocean through enhanced riverine discharge and the mobilisation of eroded materials. This will be augmented by increased precipitation in the Arctic, which will lead to more riverine transport in summer and early autumn when permafrost thaw is also most intense. These changes in hydrology will have a profound impact on the terrestrial ecosystems of deltas, as well as the freshwater balance, and biochemical fluxes in the ocean.

The Arctic Ocean is currently a large carbon sink, meaning it takes up carbon from the atmosphere and stores it in the water column or buries it in the sea floor sediments. Greater inputs of organic carbon to the ocean can change this, leading to an increased carbon flux or exchange from the ocean to the atmosphere.

When carbon dioxide reacts with water, carbonic acid is produced, which can lower the pH of the water, leading to ocean acidification. Not only does this affect the functioning of marine ecosystems, but it also reduces the ocean's ability to absorb more CO_2. Since CO_2 dissolves better in cold water, the Arctic Ocean is more sensitive to ocean acidification. The increased influx of organic carbon from river run-off, resulting from permafrost thaw, will further reduce the Arctic Ocean's capacity to absorb carbon.

Along the edge of the world

Arctic coastal classification

Arctic permafrost spans the coastlines of Alaska, Canada, Kalaallit Nunaat (Greenland), Norway, and Russia. Much of this permafrost coastline is characterised by the presence of ice in the ground and ice on the sea. As the Arctic warms, these coasts become vulnerable to erosion which changes coastal ecosystems, threatening human settlements and infrastructure. In recognition of this, a geomorphological classification scheme was developed for the more than 100,000 km of coastline bordering the Arctic Basin. It provides a baseline against which scientists can measure fluxes of sediments, carbon, nutrients, contaminants, and other parameters as these coastlines change over time.

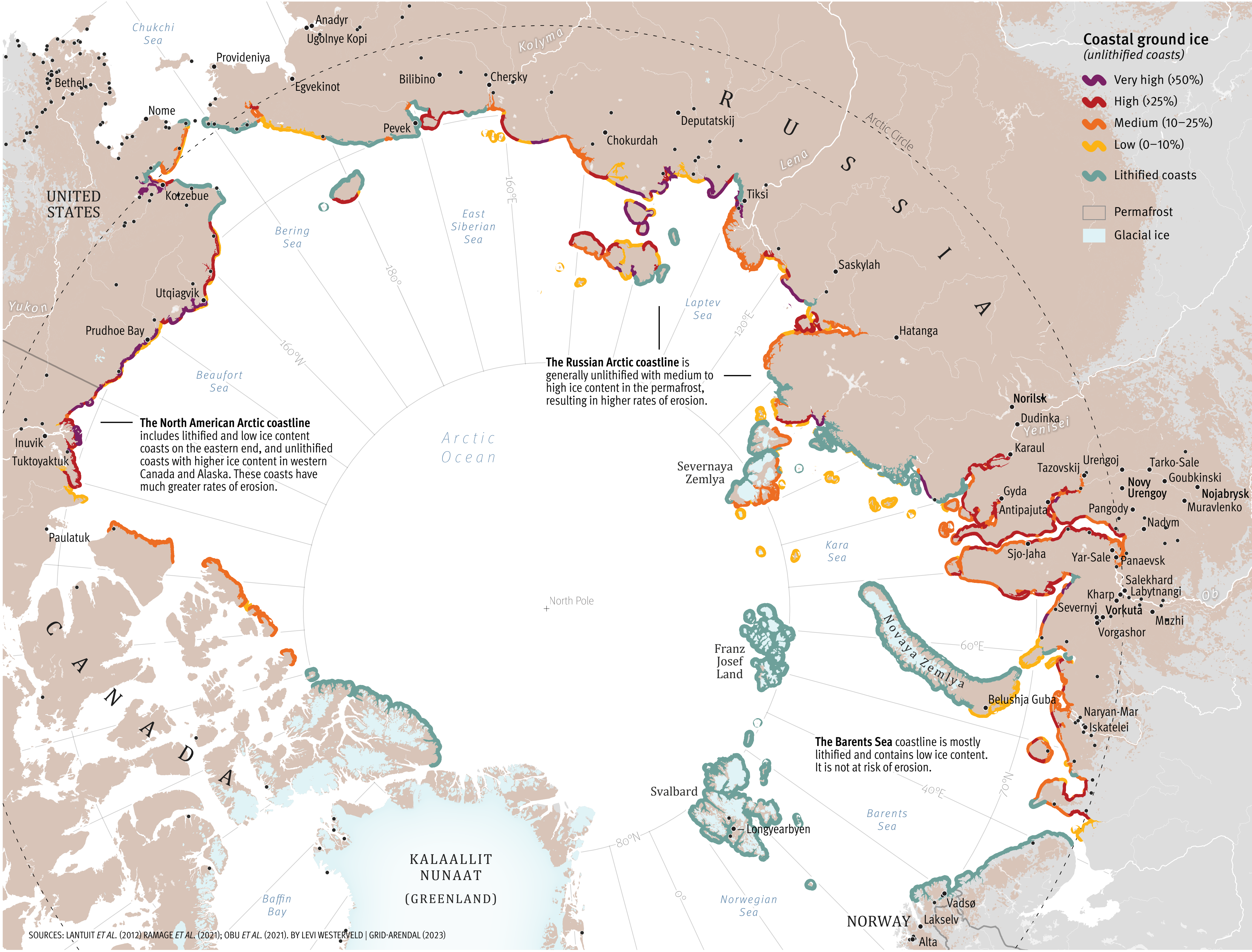
Arctic coasts show considerable variation in their geomorphology, sediment properties, and rates of erosion. Approximately 35 per cent of the classified coasts (approximately 35,000 km) are lithified (rocky). These predominantly occur in the Canadian Archipelago, northern Kalaallit Nunaat, north-western Russia (Kola Peninsula), and the islands in the Barents Sea (northern Svalbard, Franz Josef Land, and Novaya Zemlya). Lithified coastlines are characterised by low-lying rocky shores, fjords, and cliffs, and tend to contain little to no ground ice. These rocky shorelines are relatively stable with erosion occurring mostly by weathering and wave action but are also affected by freeze-thaw fracturing and direct ice action. They were mostly covered by continental ice sheets during the Last Glacial Maximum (LGM), and some are recently uncovered by slow glacial and rapid ice shelf retreat. Extensive tidewater ice fronts remain, shedding icebergs.

The greater portion of Arctic Basin coasts – 65 per cent or approximately 66,000 km – are unlithified or sedimentary. Unlithified coasts dominate the shores of the north-western Canadian Arctic, Alaska, and most of Siberia: areas that were not covered by continental ice sheets during LGM. Some unlithified coasts are characterised by large volumes of ground ice, the amount of which is determined by the glacial history of an area. Unlithified coasts in Alaska and eastern Siberia, for example, are characterised by late Pleistocene-era, ice-rich Yedoma permafrost. Common features include ice-rich permafrost bluffs, beach ridges, barrier islands, spits, deltas, and retrogressive thaw slumps. Unlithified coasts in other parts of the Arctic, such as parts of the Canadian Archipelago, Kalaallit Nunaat, and Svalbard, contain less ground ice but may be affected by anchor ice, ice ride-up, and pile-up ridging. Boulder barricades and boulder-flats demonstrate the importance of sea-ice rafting and tidal action but are largely unaffected by permafrost.

The amount and distribution of ground ice within permafrost affects thermal and mechanical erosion, as well as other geomorphological processes. As air temperature increases, soil is warmed from both the surface (top-down) and the coastal bluff or cliff face (inward from the coast) leading to rapid permafrost thaw and ground-ice melt. Unlithified coasts, especially those in ice-rich areas, are vulnerable to climate change. At some locations, yearly erosion rates can exceed 20 metres per year.

The presence of sea ice also has a great influence on permafrost coasts. As sea ice declines because of climate warming, ice-free seasons become longer, leading to increased exposure of vulnerable shorelines to more wave action. Reduced sea ice means there is a longer fetch – the distance across open water – leading to higher wave energy. Since the beginning of satellite measurements in 1979, Arctic sea ice has been declining by 13 per cent per decade, with a loss of about 80,600 km^2 per year, with the greatest declines in the last 15 years. As the open-water season becomes longer, the coastlines will be exposed to more storms later into autumn, impacting both coastal ecosystems and coastal communities and infrastructure.

While erosion is a concern along many permafrost sedimentary coasts, less research has been conducted on emerging polar coasts -- areas where the land is rising or expanding, like deltas and other sediment-accumulating landforms, leading to the development of new permafrost. Glacial isostatic adjustment is caused by the Earth's crust rebounding after being pressed down when covered by thick ice caps during the last ice age. The east coast of Canada's Hudson Bay in northern Quebec, for example, is rising at approximately 13 millimetres per year. Monitoring conducted here since 2005 shows that permafrost has been forming and deepening in land that is now exposed to a cold climate. Similar aggradation of permafrost has been documented at other sites around Hudson Bay and in the Canadian Arctic Archipelago.



SOURCES: LANTUIT *ET AL.* (2012) RAMAGE *ET AL.* (2021); OBU *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Wear and tear

Erosion of Arctic permafrost coasts

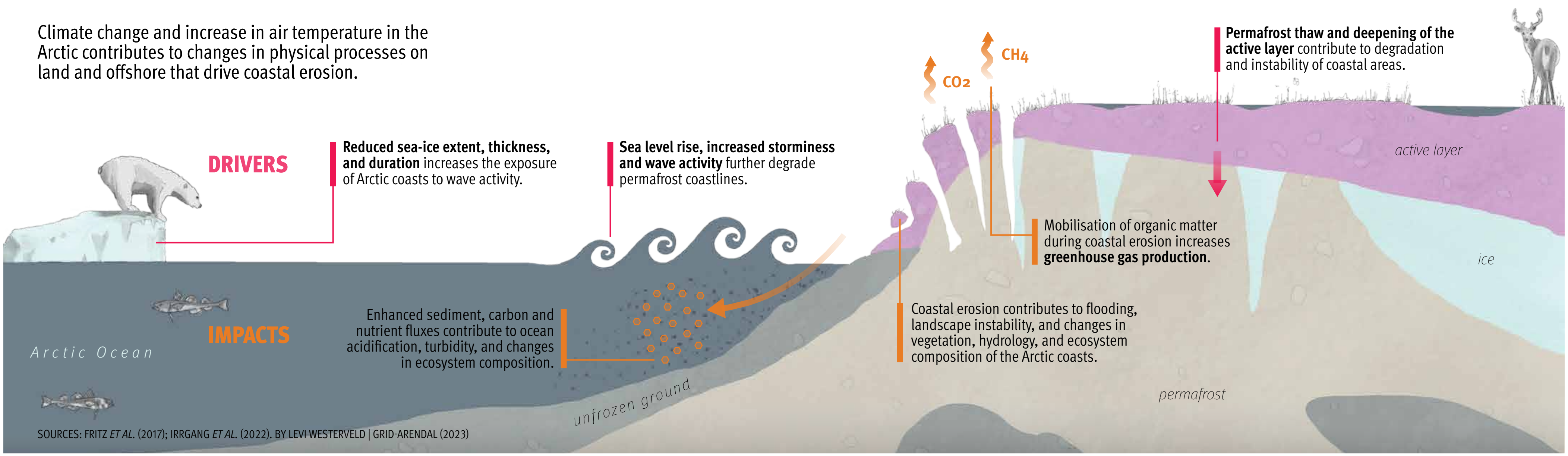
Like coastlines everywhere, the main drivers of coastal erosion in the Arctic are increasing air temperature, sea level rise, and wave action. Most coasts around the world experience physical erosion (through wave action). The Arctic coasts, however, are also affected by thermal erosion (through increasing air and water temperatures). The presence of ground ice is the major difference between Arctic coasts and all other coastlines and makes them especially vulnerable to erosion.

Unlike most other coasts in the world, **air temperature** plays a significant role in coastal change in the Arctic. Increasing temperatures affect not only the ground temperature and active layer thickness, but also sea temperature, sea ice extent, and the duration of sea ice cover. Ice-rich permafrost bluffs are particularly impacted by **thermal denudation**, the process whereby increasing air temperature and thawing permafrost cause parts of the bluff face to loosen and collapse. As coastal permafrost degrades, it may also be subject to saltwater intrusion from wave action, further increasing erosion.

Changing **sea levels**, both rising and falling, affect shorelines. Rising sea levels can exacerbate thermal abrasion as waves reach higher on the bluff face. Even temporary changes in sea levels, such as during storms, can cause changes in the shoreline and increase thermal abrasion.

Wave action depends on wind speed and direction, fetch (the distance of open water over which wind blows), and nearshore bathymetry (the measurement of underwater depth). In the Arctic, the mean annual fetch is strongly affected by the duration of the open-water season: the part of the year without sea ice. The longer the open-water season, the more erosion will occur. Some of the strongest storms occur in September and October, a time when sea ice is at its minimum extent and both the permafrost active layer and surface temperatures are at a maximum, making permafrost coasts more vulnerable to erosion.

Thermal abrasion is a mechanism whereby the water temperature together with wave energy erode ice-rich permafrost coasts. The impact of thermal abrasion on ice-rich coasts is three to four times stronger than wave action alone. In some areas, thermal denudation and thermal abrasion act together to attack the bluff top and base, respectively.



SOURCES: FRITZ *ET AL.* (2017); IRRGANG *ET AL.* (2022). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Another form of erosion known as **block failure** occurs when waves undercut sections of a cliff. The niches created by thermal abrasion can extend several metres into the cliff's base, particularly in ice-rich horizons, causing large blocks of ice-bonded sediment to collapse. In a matter of days to months, these blocks are eroded by wave action. Some of the highest erosion rates in the Arctic are the result of block failure, reaching 48.8 metres on the Beaufort Sea coast in Alaska in 2008.

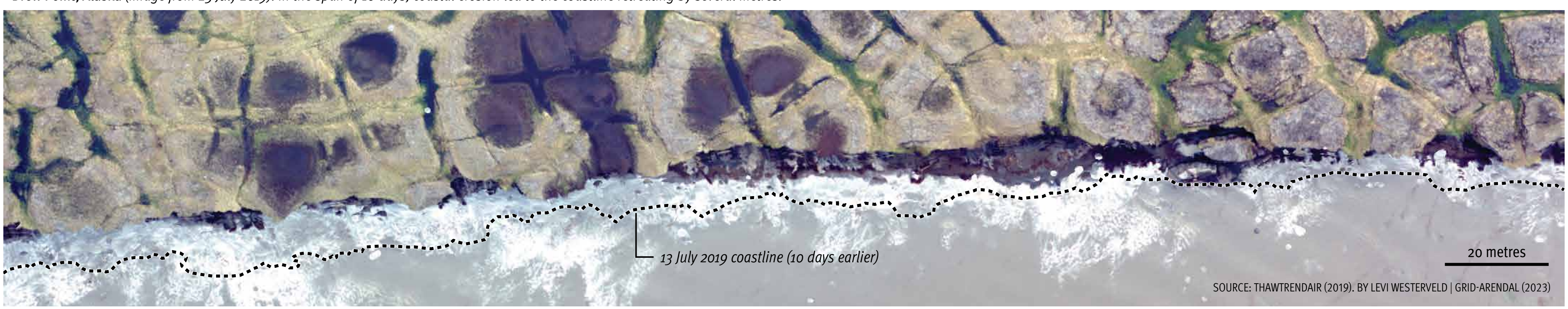
Eroding coastlines can have numerous impacts on the natural environment and human settlements. As permafrost degrades, it can release large amounts of organic carbon, nutrients, and contaminants into both the aquatic environment and the atmosphere. It is estimated that coastal erosion contributes 14 million tons of particulate organic carbon annually to the Arctic Ocean, more than the input from rivers. Coastal erosion is also responsible for 1.6 million tons of nitrogen entering the Arctic Ocean annually. Although this large influx of nutrients may increase primary production in the nearshore, the overall impact on coastal ecosystems remains poorly understood.

While some carbon from eroding coastlines will be taken up in organisms and marine sediments, it will also be released to the atmosphere. As organic carbon currently stored in permafrost is exposed by erosion, it starts to thaw and decompose, releasing carbon dioxide and methane into the atmosphere. Studies show that the emission of greenhouse gases from eroding coastal bluffs begins as soon as the carbon is exposed to seawater.

Coastal erosion can directly threaten human settlements. The community of Tuktoyaktuk on the Canadian Beaufort Sea coast, for example, has suffered extensive damage because of coastal erosion. Although many efforts have been made to protect the community from the sea, the coast has eroded to the point that numerous buildings need to be relocated further inland or they will be washed away. Coastal erosion is so severe in some locations that whole communities need relocating (e.g., Shishmaref and Kivalina in Alaska). This is not an easy proposition since the costs of relocation are high, and the cultural identities of these communities are intimately tied to their current location.

Coastal erosion is also affecting cultural heritage in the Arctic. Numerous archaeological and cultural sites across Alaska and Canada have been destroyed. Even in Kalaallit Nunaat (Greenland) and Svalbard, which are less susceptible to erosion because of their generally rocky shoreline, cultural artefacts along their coasts are at risk as the climate warms.

Drew Point, Alaska *(image from 23 July 2019). In the span of 10 days, coastal erosion led to the coastline retreating by several metres.*



1 In the summer, as the sun and higher air temperatures heat the headwall of the retrogressive thaw slump, permafrost thaws and flows towards the sea.
Snow from the previous winter which has not yet melted can be seen on parts of the headwall.
50 metres
N
2 Mud pools and different material accumulate down from the headwall in the area called the slump floor.
3 Melting from snow and ice in the permafrost, as well as rain, creates a drainage system that transports sediments from the retrogressive thaw slump to the coast.
4 High sediment supply released into the sea results in high levels of water turbidity, which affects the availability of light for organisms in the sea.

SOURCE: MODIFIED FROM VIEIRA *ET AL.* (2018). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Eating into the landscape

Retrogressive thaw slumps

One of the features of thawing permafrost is the appearance of retrogressive thaw slumps. These are large, curved depressions along coastlines, riverbanks, lakeshores, and hill slopes. These slumps occur when massive ice bodies in permafrost are exposed to warm air, making them vulnerable to rapid thaw and erosion. As the ice melts, a slurry of water and sediment moves downslope and the headwall retreats – or retrogresses – inland. The thawing permafrost has the potential to trigger the release of greenhouse gases and contaminants that have been stored in the permafrost, sometimes for thousands of years. Retrogressive thaw slumps are common in the ice-rich permafrost of the western Canadian Arctic, the Yedoma of eastern Siberia, and the central Yakutia region of Russia where they are referred to as thermo-terraces or thermo-cirques. They can be several hundreds of metres wide and can retrogress several hundreds of metres inland.

As the climate warms, retrogressive thaw slump activity is increasing. On the Taimyr Peninsula, located between the Kara and Laptev Seas in Siberia, retrogressive thaw slumping has increased 43-fold between 2010 and 2021. In this same period, carbon mobilisation increased 28-fold. This increase coincides with an extreme heat wave in northern Siberia in the summer of 2020, in which the region experienced record-breaking temperatures (38 °C). As the climate continues to warm, heatwaves in the Arctic can be expected to occur more often, exacerbating the impacts on permafrost.

Despite the considerable risks associated with increasing retrogressive thaw slump activity, it is still poorly accounted for in the Arctic carbon cycle.


SOURCE: MODIFIED FROM VIEIRA *ET AL.* (2018). BY ALEX TAIT | GRID-ARENDAL (2023)

PORTRAIT INUVIALUIT SETTLEMENT REGION COMMUNITY-BASED MONITORING PROGRAM, INUVIK, NWT

Angus Alunik

My name is Angus Alunik, and I was born by a small creek they call “Awa” in the Mackenzie Delta in 1952. Soon after my birth, my mother passed away, so I was adopted a few days later by my adoptive parents, Ishmael and Ruth. Luckily, they maintained a good relationship with my biological father, so I was able to learn about my roots.

We lived in the bush most of the time, until 1969 or 1970 when we moved to Stringer Hall. In May, before the ice would melt, my father would take me to the bushcamp for the spring. I’d spend a lot of time hunting with him because he wanted me to learn the ropes. My brother mostly stayed in school. While the ice was still there, we would often leave the cabin and set up a tent for the three of us. We’d walk around, leaving the dogs behind, setting up muskrat traps and sometimes even catch beavers. Years ago, the ice would stay there until June.

I remember, years ago, my dad would make a small pit to keep stuff frozen. You dig a bit until you hit permafrost and you put fish and meat in there. A lot of people built ice houses. They would put logs and then mud around it and then make a little door. It used to be good then, but years later I noticed that you had to dig deeper and deeper to hit permafrost. It’s really thawed.

I also see a lot of erosion, not only at home where my camp is, but all along the foothills from Inuvik right down to Reindeer Station.

After I moved from Edmonton, I built a house not too far from where my dad’s log cabin was. When I first built my house, there was a lake behind me, with another lake towards the Mackenzie River on the left side. At the time, it seemed okay as we didn’t see any signs of erosion. But after a decade or so, I noticed that we started to lose riverbank. We had gone to bed for the night, I had the generator running about 100 metres from the bank. This was in the summer of 2000. The next morning, while we were having breakfast, my wife said, “I thought your generator was over there.” I looked out in shock. What?! Where is my generator? I walked over and saw we’d lost a part of the riverbank the size of the house. It just disappeared.

Ever since then we’ve been losing riverbank all the time. Every few years, I’d have to borrow a winch to pull the house back because the riverbank was so close. Then, suddenly, the lake behind us was gone, drained into the channel. From there, it got worse. About five years ago, I lost my whole house. The cabin that I built went over the bank and I lost everything in it.

Some people were already having meetings about this, but I wasn’t really involved in any of them. I just started going to meetings recently, but how can you fix Mother Nature? I don’t think you can. I think it’s going to keep coming. So, for me, I just live with it. I mean, why get mad about it? You can have all the meetings you want and everything and try to fix it. But I don’t think we can. I think, now that it’s started, we won’t ever stop it.

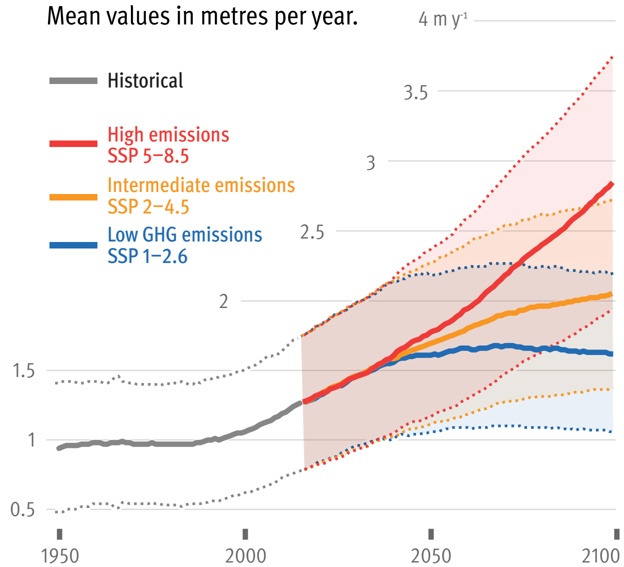
Losing ground

Projected rates of Arctic coastal erosion

Arctic coasts are subject to erosion by mechanical forces (e.g., wave action) and thermal forces (e.g., increasing air temperatures). These forces work together to thaw permafrost, melt ground ice, and wear away material at the coast. As the Arctic continues to warm, permafrost coasts thaw, potentially releasing greenhouse gases into the atmosphere and further exacerbating the drivers of coastal erosion.

The rate of coastal erosion has been increasing in recent decades. Between 1850 and 1950, the mean rate of coastal erosion was estimated at 0.9 metres per year, considering only the erosive segments, or 0.5 metres per year of the 400,000 km of coasts facing the Arctic Basin. By the end of this century, it is estimated that the mean rate of coastal erosion for both rocky and sedimentary coasts will increase to between 2 metres per year under an intermediate climate change scenario, and 2.6 metres per year under a high climate change scenario. Current modelling shows that coastal erosion in the Arctic will likely exceed its historical range by around 2050, and possibly even earlier.

Modelled Arctic coastal erosion rates
Mean values in metres per year.

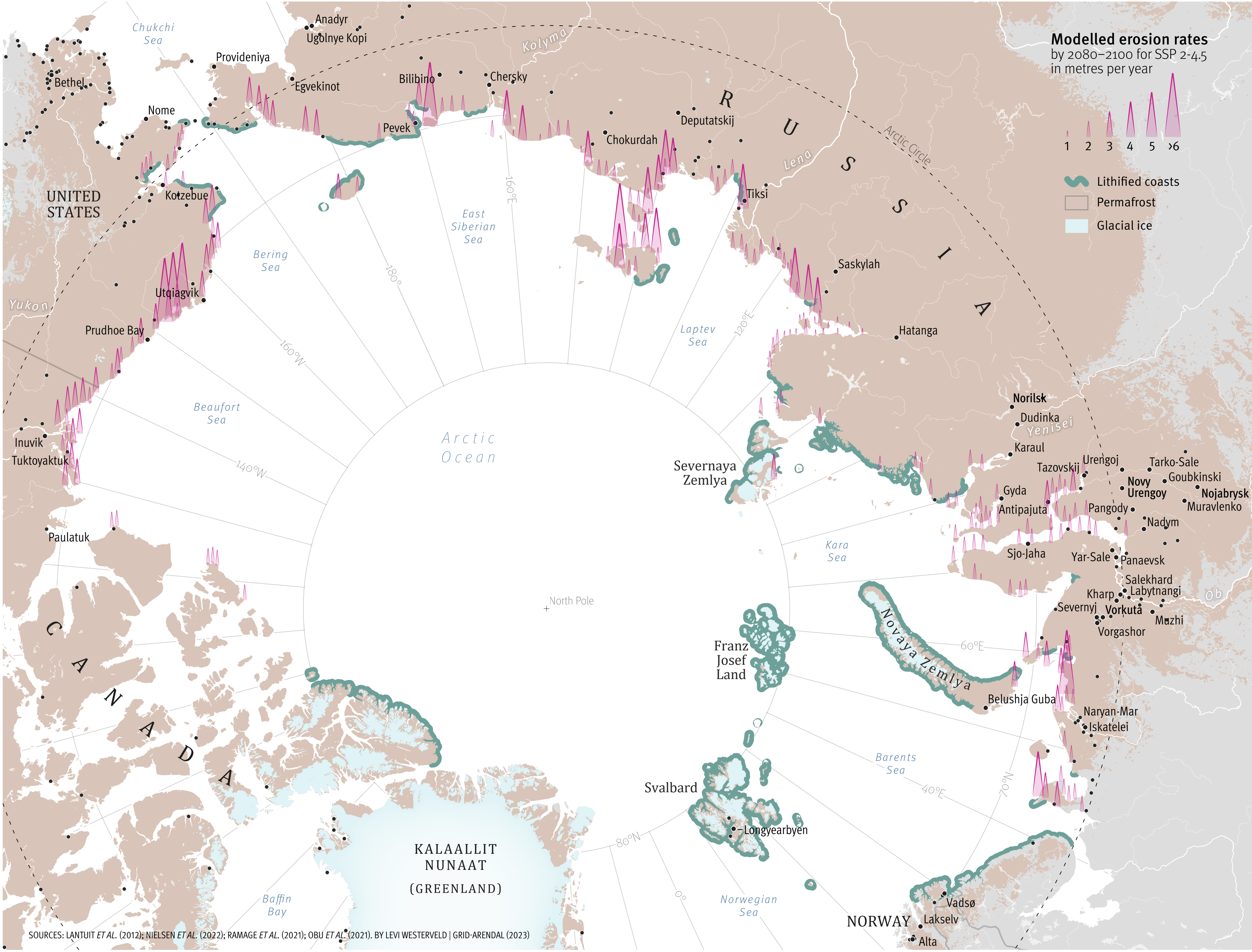


SOURCE: NIELSEN *ET AL.* (2022). ADAPTED BY LEVI WESTERVELD | GRID-ARENDAL (2023)

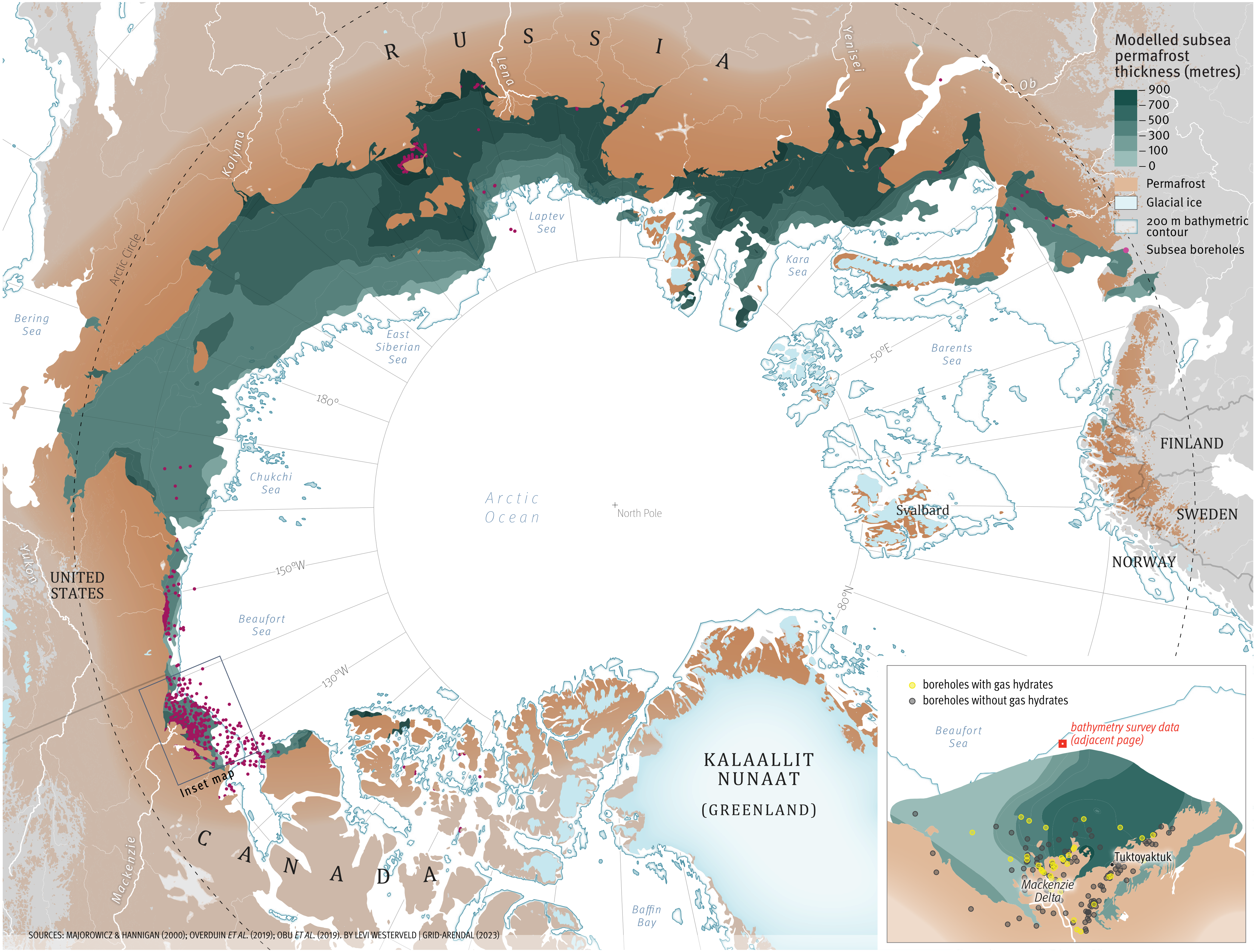
Coastal erosion releases large amounts of organic carbon into the ocean. The greatest current and projected losses of organic carbon – about 75 per cent – are in the Laptev and East Siberian Seas of Russia. Coastal erosion in this region is very high, up to 20 metres per year. This region is also dominated by ice-rich Yedoma deposits and high cliffs with high organic carbon content. The next highest losses are along the Beaufort Sea coast of Canada and Alaska, accounting for about 12 per cent of the Arctic total. The remainder of organic carbon loss in the Arctic comes from the other marginal Arctic seas.

There are numerous uncertainties surrounding future coastal erosion but even in low emissions scenarios, erosion rates are projected to increase until at least the middle of the century. In the higher greenhouse gas emissions scenarios, however, coastal erosion would continue to increase beyond 2050, releasing between 2.3 million tons (intermediate emissions scenario) and 4.2 million tons (high emissions scenario) of organic carbon annually. Starting from the year 1850 up to 2100, it has been estimated that about 2 trillion tons of carbon will be lost from permafrost as a result of coastal erosion. This amounts to 17–26 per cent of the overall carbon losses from thawing permafrost across the Arctic. But there are considerable uncertainties in these estimates. The actual losses will depend on the degree of warming that eventually occurs as well as the impacts of that warming on the ecological and geomorphological processes associated with coastal erosion.

Coastal erosion is important to marine primary production in the Arctic, as it releases and transports organic carbon into the aquatic environment. The fate of the increased organic carbon in the Arctic is still relatively unknown. It may settle into marine sediments where decomposition will be very slow (over millennia), or it may be partially decomposed before entering the ocean, releasing greenhouse gases into the atmosphere. It is also possible that it will degrade in the water column or be transported further away. Degradation in the water column happens through a process of mineralisation, which changes the ocean alkalinity and pH and increases dissolved inorganic carbon and nutrient supplies, all of which impacts primary production and air-sea carbon fluxes.



SOURCES: LANTUIT *ET AL.* (2012); NIELSEN *ET AL.* (2022); RAMAGE *ET AL.* (2021); OBU *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



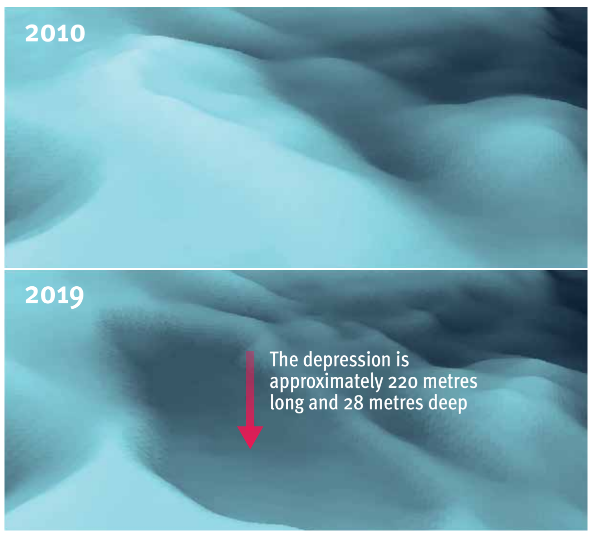
SOURCES: MAJOROWICZ & HANNIGAN (2000); OVERDUIN *ET AL.* (2019); OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Beneath the waves

Changes in subsea permafrost

Permafrost not only occurs on land but under the ocean floor too. Subsea permafrost is relict terrestrial permafrost that formed during the Last Glacial Maximum (LGM) when the global sea level was more than 100 metres lower than present day, exposing the present shelf areas. As the ice sheets retreated and the sea level rose, the permafrost that had formed on land was submerged under the ocean. Like terrestrial permafrost, subsea permafrost is composed of frozen sediment and rock, and may or may not contain ice. There is only about a fifth as much permafrost under the ocean as there is on land in the northern hemisphere. Most subsea permafrost occurs in northern Siberia, with some extending to Alaska and north-western Canada, land areas that were exposed during much of the last glacial period. The thickness of subsea permafrost varies across the Arctic. In most locations, it is less than 200 metres thick, but it can reach greater depths. Modelling suggests that permafrost in the Laptev, Kara, and East Siberian Seas may be over 700 metres thick in places.

Bathymetric surveys show that seafloor depth on the Canadian Beaufort Sea Shelf increased up to 28 metres between 2010 and 2019.



SOURCE: PAULL *ET AL.* (2022). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

There are numerous landforms that may be associated with subsea permafrost. **Pingo-like features** are found in some shelf areas of the Arctic Ocean, are similar in size and form to terrestrial pingos, and can contain ground ice. They are found in some shelf areas of the Arctic Ocean. **Mud volcanoes** are formed by the movement of sediments, fluids, and gases up to the sea floor. They can reach 40 metres in height and more than 500 metres in diameter. The unique environment created by mud volcanoes supports a rare community of tube worms in the Beaufort Sea. **Pockmarks** may be observed on the sea floor in areas where gases were recently released.

High-resolution bathymetric surveys in the Canadian Beaufort Sea have found large, newly created depressions on the sea floor, about 180 kilometres offshore and in water 120–150 metres deep. The largest depression is 29 metres deep, 225 metres long, and 95 metres wide. It is believed that these depressions are the result of permafrost thawing – similar to slumps and craters forming on land. While climate change is a driver of permafrost thawing on land, the limited data on sea floor temperature in this region do not show warming. Instead, these changes are thought to be the result of heat found in slow moving groundwater below the permafrost.

Current estimates suggest that approximately 2,800 billion tons of organic carbon has accumulated in subsea permafrost over the last 450,000 years. This is more than twice the amount of organic carbon on land (estimated at 1,460–1,600 billion tons) and more than four times the carbon in our atmosphere. It is not known, however, whether it will be decomposed by microbes easily or quickly enough to have a correspondingly large climate effect.

Within and below subsea permafrost are gas hydrates, a solid form of gas and water. Gas hydrate molecules are made up of gas molecules, usually methane, within a cage of water molecules. The methane may originate from either deep deposits of oil and other hydrocarbons or from ancient microbial activity. They are only stable under high pressure, such as below the ocean floor and at very low temperatures.

Although there is interest in gas hydrates as a future energy source, they present a potentially significant source of greenhouse gases. If methane hydrates destabilise, they will release more than 160 times their volume as methane, one of the strongest greenhouse gases. It is not clear how much gas hydrate there is in subsea permafrost, but a conservative estimate is 20 billion tons of carbon. Better estimates are also needed of how much methane occurs as free gas in sediments.

Permafrost acts as a barrier to prevent gases from reaching the surface. If gases are released from, for example, oil deposits deep below the ocean floor, they become trapped by the subsea permafrost as they migrate upward through the sediment. But as subsea permafrost thaws, it starts to release the trapped carbon dioxide and methane which may reach the atmosphere, contributing to global warming.

© Katie Orlinsky

Arctic Ripples

Impacts of Permafrost

Feeling the heat

Permafrost thaw impacts on infrastructure

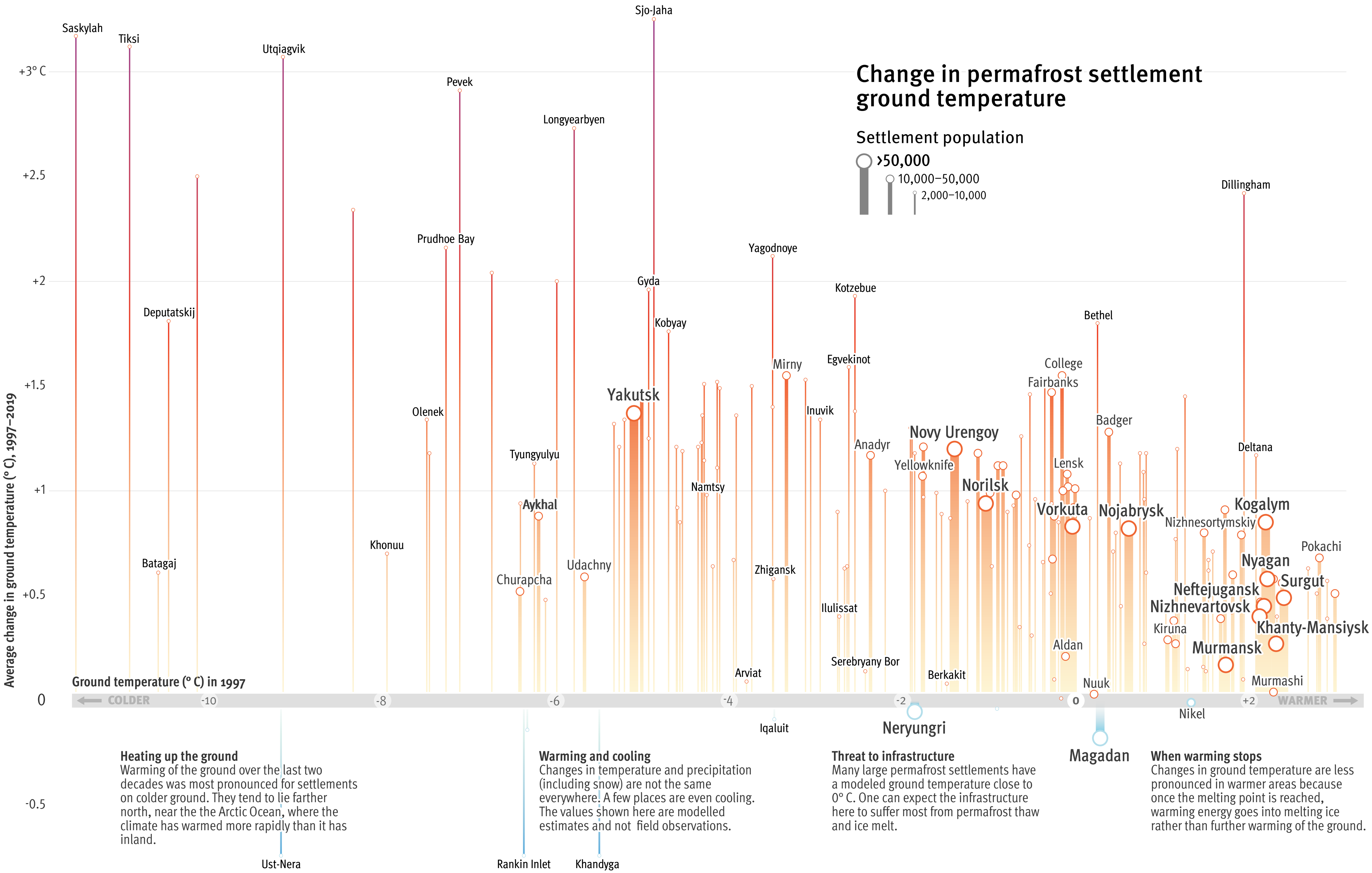
Permafrost has always presented an engineering challenge for infrastructure. Human settlements, industrial facilities, and networks for transportation, communication, and energy all need a stable surface on which to function. When infrastructure lies on top of permafrost, construction must accommodate the annual thawing of the active layer to keep structures secure while not disturbing the thermal balance of the frozen ground. Even just erecting a structure directly on permafrost can generate localised heat, increasing the thaw while decreasing the ground's bearing capacity. As the climate warms and permafrost softens, the impacts on infrastructure may pose significant risks to the safety and security of people who live and work in the Arctic.

The scale of this problem is immense: 70 per cent of all Arctic residential, industrial, and transport infrastructure is in areas where near-surface permafrost thaw is likely by 2060. Currently, almost 5 million people live in 1,150 settlements located on permafrost, the majority concentrated in just over 500 settlements located in zones of sporadic permafrost. By 2050, 42 per cent of the 1,150 permafrost settlements are projected to become permafrost-free due to thawing, affecting an estimated 3.3 million people.

Infrastructure is most prone to damage in areas with high ground-ice content and thick deposits of frost-susceptible sediments as well as in areas of "warm permafrost" where permafrost thaw is most pronounced and where most of the infrastructure is located. As permafrost thaws, it can become unstable, shift, and resettle unevenly. This can lead to both ground subsidence and decreased bearing capacity, which causes cracks, deformations, or the collapse of buildings, pipelines, and other infrastructure. To address this, most of the infrastructure on permafrost has been built with the goal of maintaining the frozen state of the ground to give it "freezing strength or bearing capacity". Other methods of building on permafrost include active cooling or modifying the ground properties prior to construction, such as by excavating thawing soil. Another option to actively cool the ground is the insertion of thermosyphons underground. Thermosyphons, like refrigerators, are closed heat exchangers based on gas-liquid flow circulation. This method, however, is expensive and thus not frequently used.

Some of the most striking examples of infrastructure damage from permafrost thaw have been to buildings in the Russian Arctic, where most of the infrastructure was built with the goal of keeping the permafrost beneath it in a frozen state. Housing blocks were typically built with a ventilated airspace (crawl space) beneath elevated buildings supported by concrete piles to prevent heat from the buildings reaching the ground. Unlike open crawl spaces where permafrost temperature is close to the mean annual air temperature, the air in poorly ventilated crawl spaces is warmer and heats the permafrost below. As permafrost warms across Arctic settlements, the impacts of poor design will worsen. In some Russian cities, such as Vorkuta in the Komi Republic, 80 per cent of all buildings now experience deformations in their building structure due to thawing permafrost, along with other factors such as poor construction quality and poor maintenance. Many buildings have been abandoned or demolished because they are unsafe to live in or because the structural failures make it impossible to retain interior heat during the cold winters.

Linear infrastructure is also subject to damage from changes in permafrost. In summer, for example, roads can experience subsidence through the thawing of permafrost and loss of bearing strength on fine-grained sediments. In the winter, frost heaving may cause substantial dips, waves, cracks, and potholes in roadways, requiring constant maintenance and repaving. Groundwater can also seep into the embankments underneath roads, increasing the temperature of the soil and leading to further permafrost degradation. Pipelines, railways, and airport runways experience similar challenges. Railway lines often require costly upkeep. The necessity to maintain low gradients means that they are usually located in lowland areas where ground-ice content is often high.



SOURCE: RAMAGE *ET AL.* (2021); OBU *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Risky business I

North American Arctic and Kalaallit Nunaat (Greenland)

Sparsely populated, the permafrost regions of North America and Kalaallit Nunaat (Greenland) account for just under 8 per cent of the entire Arctic permafrost population. These regions feature small individual houses and relatively lightweight administrative and industrial facilities. Buildings represent by far the most important infrastructure asset in these regions. Canada's road network represents a significant proportion of infrastructure value, but apart from the highways in the southern Northwest Territories and Yukon, and the road from Dawson to Inuvik and Tuktoyaktuk, the network is restricted to local roads in individual communities. Because of these restrictions, remote communities in Alaska, northern Canada, and Kalaallit Nunaat depend on ports and airports.

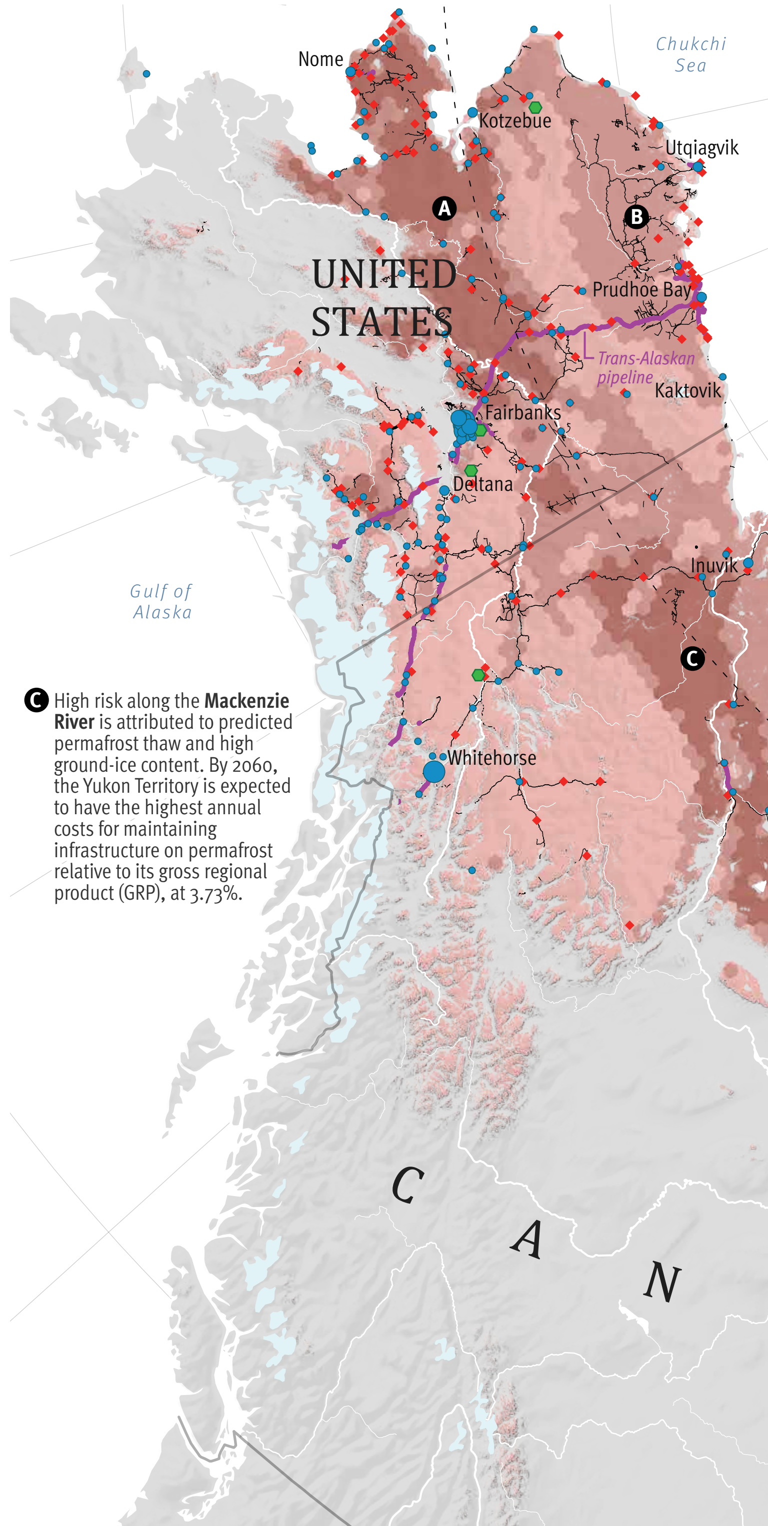
In Alaska, permafrost constitutes 80 per cent of the land surface. The greatest short-term risks to infrastructure over the coming decades are found in the discontinuous permafrost zone in the interior (central and western) parts of the state. The mean annual temperatures of Alaska's interior are currently around -2 °C. By 2050, they are projected to increase to +2 °C, indicating that the permafrost in this area will be actively degrading.

In Canada, permafrost underlies about 50 per cent of the ground surface, most of it in the Arctic. Many communities in the Canadian Arctic are located on emergent coasts. These uplifted former seabed deposits contain saline permafrost, which has reduced bearing capacity. Across the country, much of the residential, institutional, industrial, and transport infrastructure has been built on sensitive permafrost, i.e., areas with warmer, ice-rich permafrost. Amid climate change, the Northwest Territories, Nunatsiavut, Nunavik, and Nunavut face the widespread challenges of infrastructure degradation, increased maintenance requirements, and the dire need for adaptation.

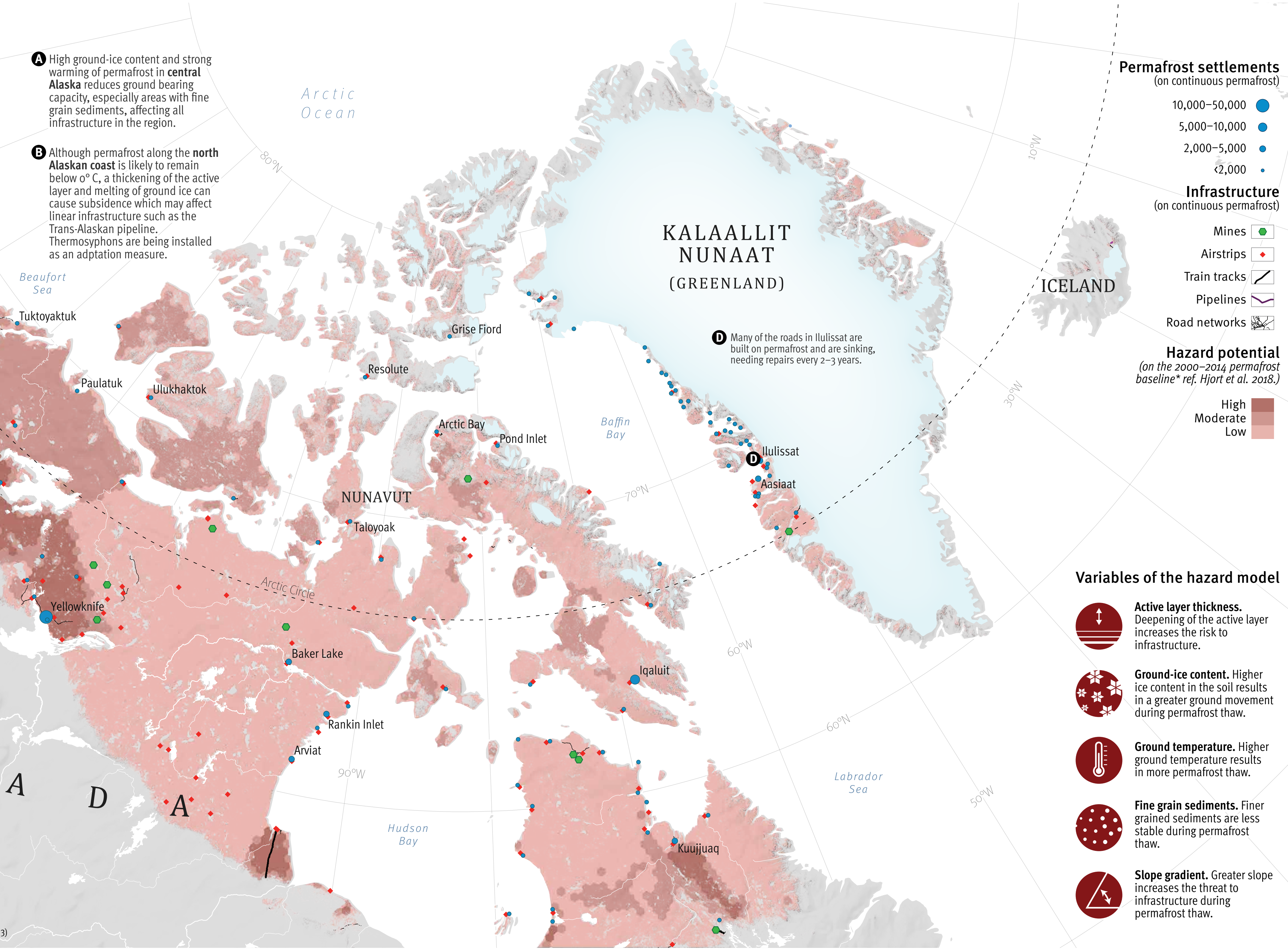
In Kalaallit Nunaat, most of the ground that is not bedrock or covered by inland ice is exposed to permafrost thaw. While most houses and buildings in the country are built on bedrock, the roads and airports lie over permafrost, putting them more at risk than any other part of Kalaallit Nunaat's infrastructure.

Across these three regions where permafrost is already thawing, infrastructure needs constant maintenance and repair. This need is increasing, whether for airstrips or for highways such as the Alaska Highway in the Yukon, the Dempster Highway (Yukon, Northwest Territories), and the newly constructed Inuvik-to-Tuktoyaktuk Highway (Northwest Territories).

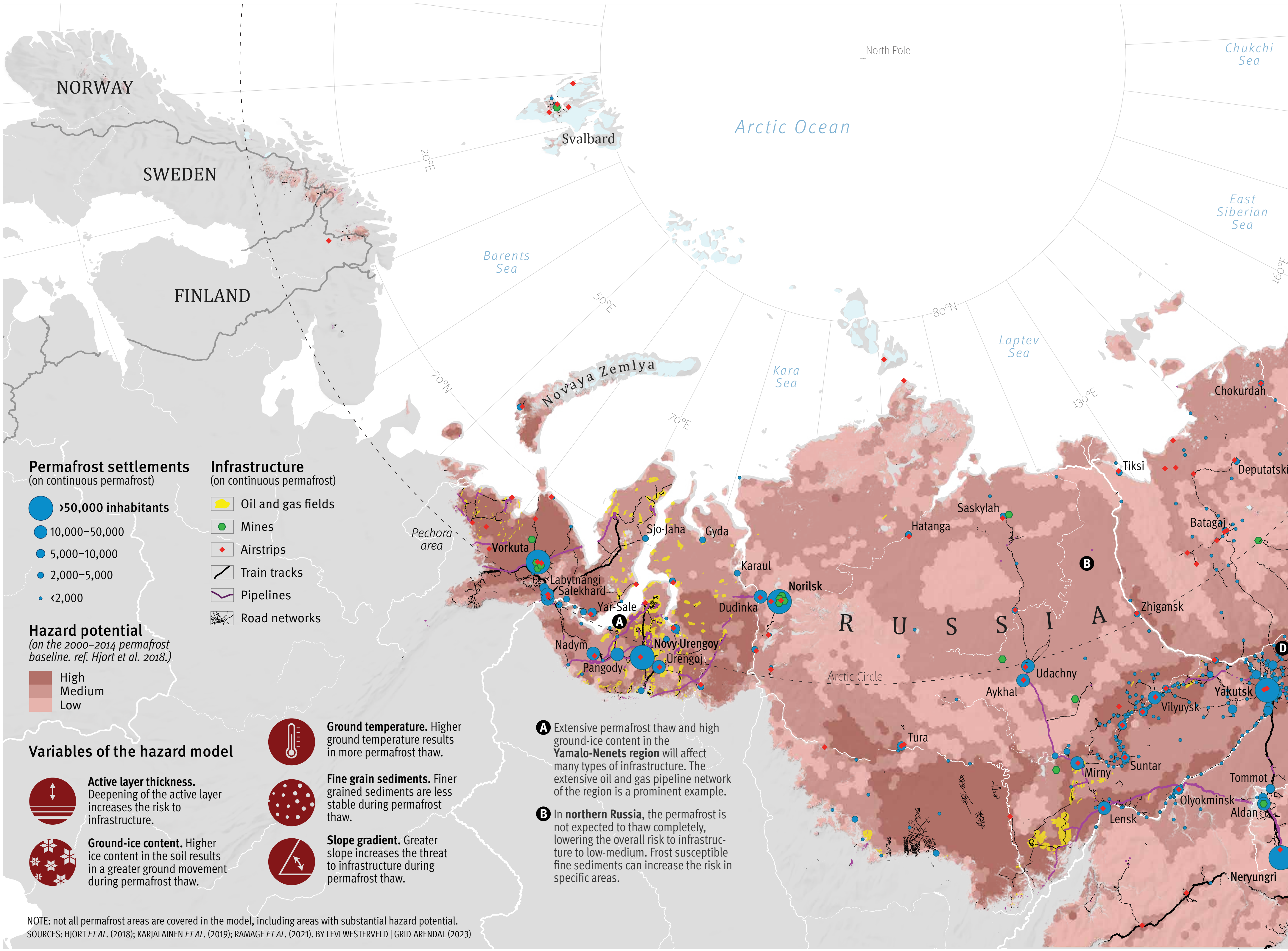
Permafrost degradation has a heavy cost: the estimated economic impacts of infrastructure damage across the circumpolar Arctic in these regions are projected to exceed USD 276 billion over the next 40 years under the higher-emission scenario. In the future, infrastructure is expected either to have a shorter lifespan or cost more to maintain. By 2060, the overall costs are estimated to increase by one-third for both Alaska and Canada (data unavailable for Kalaallit Nunaat), with pipelines having the highest estimated life cycle maintenance costs (60 per cent increase in cost by 2060), followed by roads, railways, airports (approximately 40 per cent each), and buildings (12 per cent).



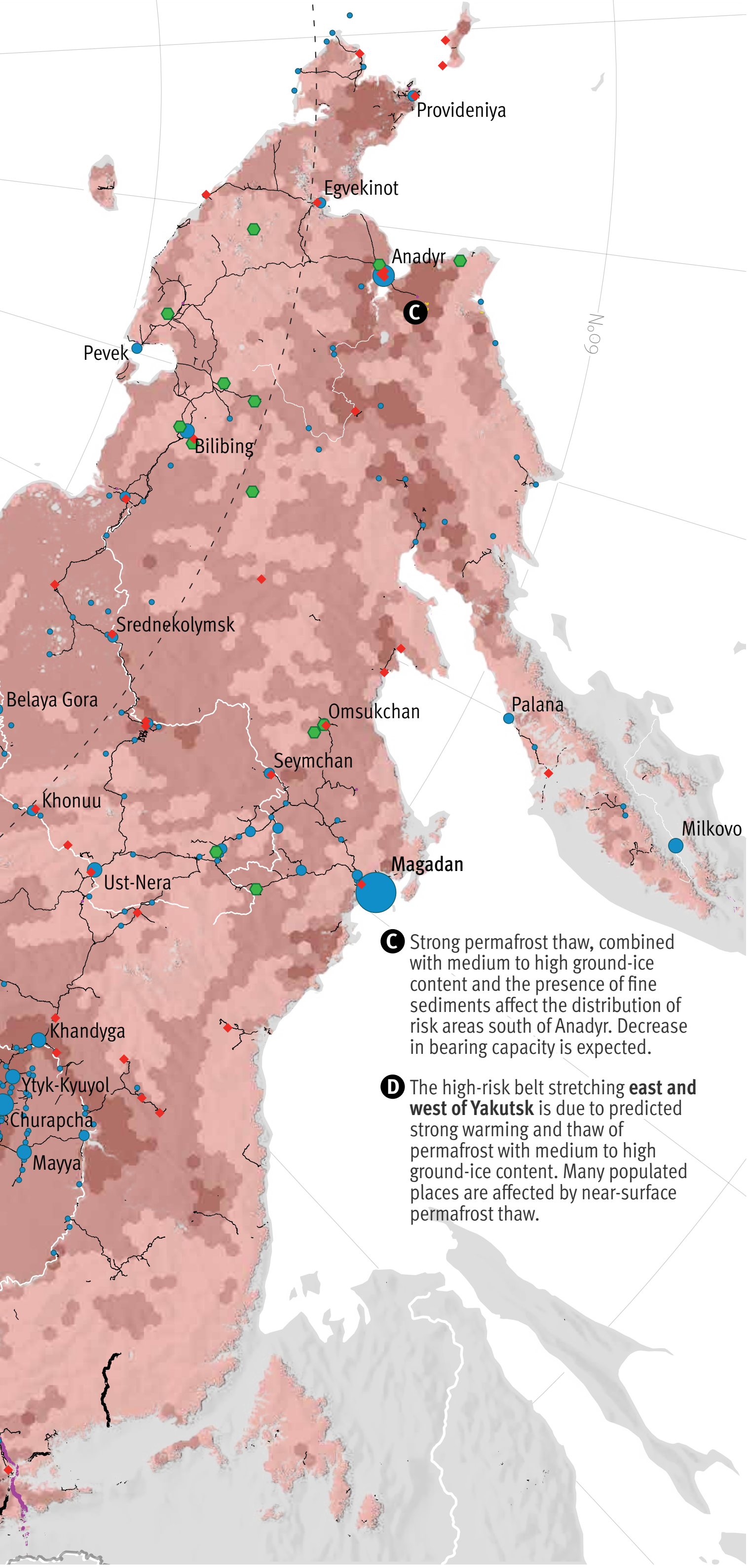
NOTE: not all permafrost areas are covered in the model, including areas with substantial hazard potential.
SOURCES: HJORT *ET AL.* (2018); KARJALAINEN *ET AL.* (2019); RAMAGE *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (202



A High ground-ice content and strong warming of permafrost in central Alaska reduces ground bearing capacity, especially areas with fine grain sediments, affecting all infrastructure in the region.
B Although permafrost along the north Alaskan coast is likely to remain below 0° C, a thickening of the active layer and melting of ground ice can cause subsidence which may affect linear infrastructure such as the Trans-Alaskan pipeline. Thermosyphons are being installed as an adptation measure.
Arctic Ocean
Beaufort Sea
80°N
Tuktoyaktuk
Paulatuk
Ulukhaktok
Grise Fiord
Resolute
Arctic Bay
Pond Inlet
NUNAVUT
Taloyoak
Arctic Circle
Yellowknife
Baker Lake
Rankin Inlet
Arviat
Iqaluit
Kuujjuaq
A D A
90°W
Hudson Bay
Baffin Bay
Labrador Sea
70°N
60°W
60°N
50°W
30°W
10°W
KALAALLIT NUNAAT
(GREENLAND)
D Many of the roads in Ilulissat are built on permafrost and are sinking, needing repairs every 2–3 years.
Ilulissat
Aasiaat
ICELAND
Permafrost settlements
(on continuous permafrost)
10,000–50,000
5,000–10,000
2,000–5,000
‹2,000
Infrastructure
(on continuous permafrost)
Mines
Airstrips
Train tracks
Pipelines
Road networks
Hazard potential
(on the 2000–2014 permafrost baseline* ref. Hjort et al. 2018.)
High
Moderate
Low
Variables of the hazard model
Active layer thickness. Deepening of the active layer increases the risk to infrastructure.
Ground-ice content. Higher ice content in the soil results in a greater ground movement during permafrost thaw.
Ground temperature. Higher ground temperature results in more permafrost thaw.
Fine grain sediments. Finer grained sediments are less stable during permafrost thaw.
Slope gradient. Greater slope increases the threat to infrastructure during permafrost thaw.



NORWAY
SWEDEN
FINLAND
Svalbard
North Pole
Arctic Ocean
Chukchi Sea
East Siberian Sea
Barents Sea
Kara Sea
Laptev Sea
Novaya Zemlya
Pechora area
20°E
50°E
70°N
70°E
80°N
130°E
160°E
Arctic Circle
R U S S I A
Vorkuta
Labytnangi
Salekhard
Yar-Sale
Sjo-Jaha
Gyda
Karaul
Norilsk
Dudinka
Nadym
Pangody
Novy Urengoy
Urengoj
Hatanga
Saskylah
Tiksi
Chokurdah
Deputatskij
Batagaj
Zhigansk
Udachny
Aykhal
Yakutsk
Vilyuysk
Tura
Mirny
Suntar
Tommot
Olyokminsk
Aldan
Lensk
Neryungri
A
B
D
Permafrost settlements
(on continuous permafrost)
>50,000 inhabitants
10,000–50,000
5,000–10,000
2,000–5,000
<2,000
Infrastructure
(on continuous permafrost)
Oil and gas fields
Mines
Airstrips
Train tracks
Pipelines
Road networks
Hazard potential
(on the 2000–2014 permafrost baseline. ref. Hjort et al. 2018.)
High
Medium
Low
Variables of the hazard model
Active layer thickness. Deepening of the active layer increases the risk to infrastructure.
Ground-ice content. Higher ice content in the soil results in a greater ground movement during permafrost thaw.
Ground temperature. Higher ground temperature results in more permafrost thaw.
Fine grain sediments. Finer grained sediments are less stable during permafrost thaw.
Slope gradient. Greater slope increases the threat to infrastructure during permafrost thaw.
A Extensive permafrost thaw and high ground-ice content in the Yamalo-Nenets region will affect many types of infrastructure. The extensive oil and gas pipeline network of the region is a prominent example.
B In northern Russia, the permafrost is not expected to thaw completely, lowering the overall risk to infrastructure to low-medium. Frost susceptible fine sediments can increase the risk in specific areas.
NOTE: not all permafrost areas are covered in the model, including areas with substantial hazard potential.
SOURCES: HJORT ET AL. (2018); KARJALAINEN ET AL. (2019); RAMAGE ET AL. (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Risky business II

The Russian Federation and Scandinavian Arctic

Russia will likely experience the most severe impacts of permafrost thaw. Not only does the nation have the highest number of settlements in the Arctic, but it also has the highest percentage located on permafrost (60 per cent of all Arctic settlements and 90 per cent of all Arctic inhabitants, respectively).

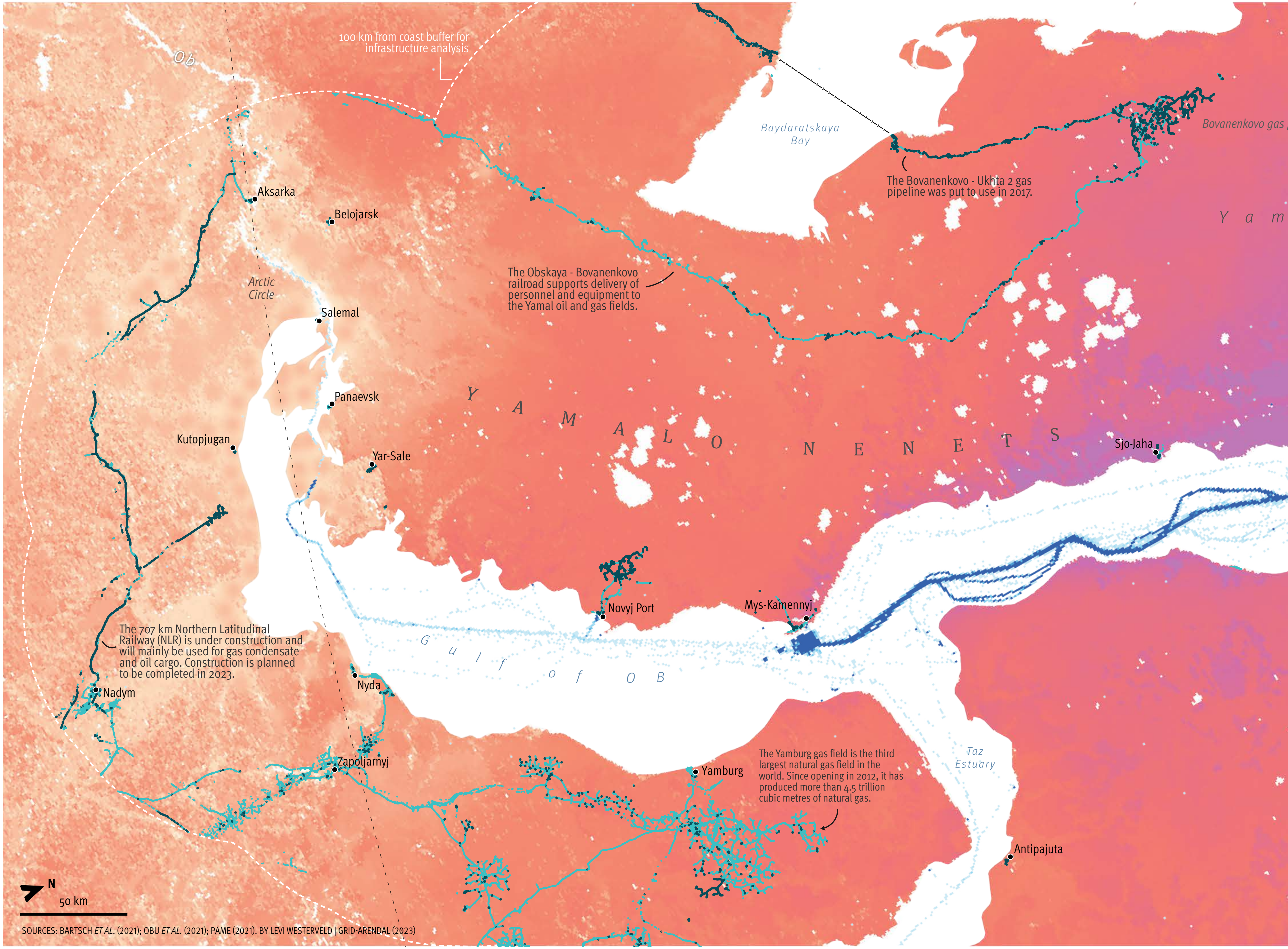
The Russian Arctic is also more urbanised and industrialised, encompassing the large cities of Norilsk, Vorkuta, and Yakutsk, which are characterised by large apartment blocks, centralised networks of heating and utilities, and large industrial facilities. High-risk areas in Russia include the north-western parts of the Ural Mountains as well as north-western and central Siberia.

Infrastructure failure is already very common across the Russian Arctic: by the early 2000s, an estimated 10 per cent of structures in the cities of Norilsk and Yakutsk and 80 per cent of structures in Vorkuta had suffered some form of deformation. Not all infrastructure damage can be directly blamed on permafrost thaw though. The collapse of the Soviet Union and worsening socioeconomic conditions in the years after led to the dismantling of permafrost monitoring infrastructure. Other factors include poor building design and construction, a lack of maintenance, and ageing infrastructure, as many buildings are being used beyond their anticipated lifespan. Consequences include the infiltration of hot water into permafrost from broken heating pipes, poor drainage, and ponding, as well as the low freeze-thaw resistance of the concrete foundation piles.

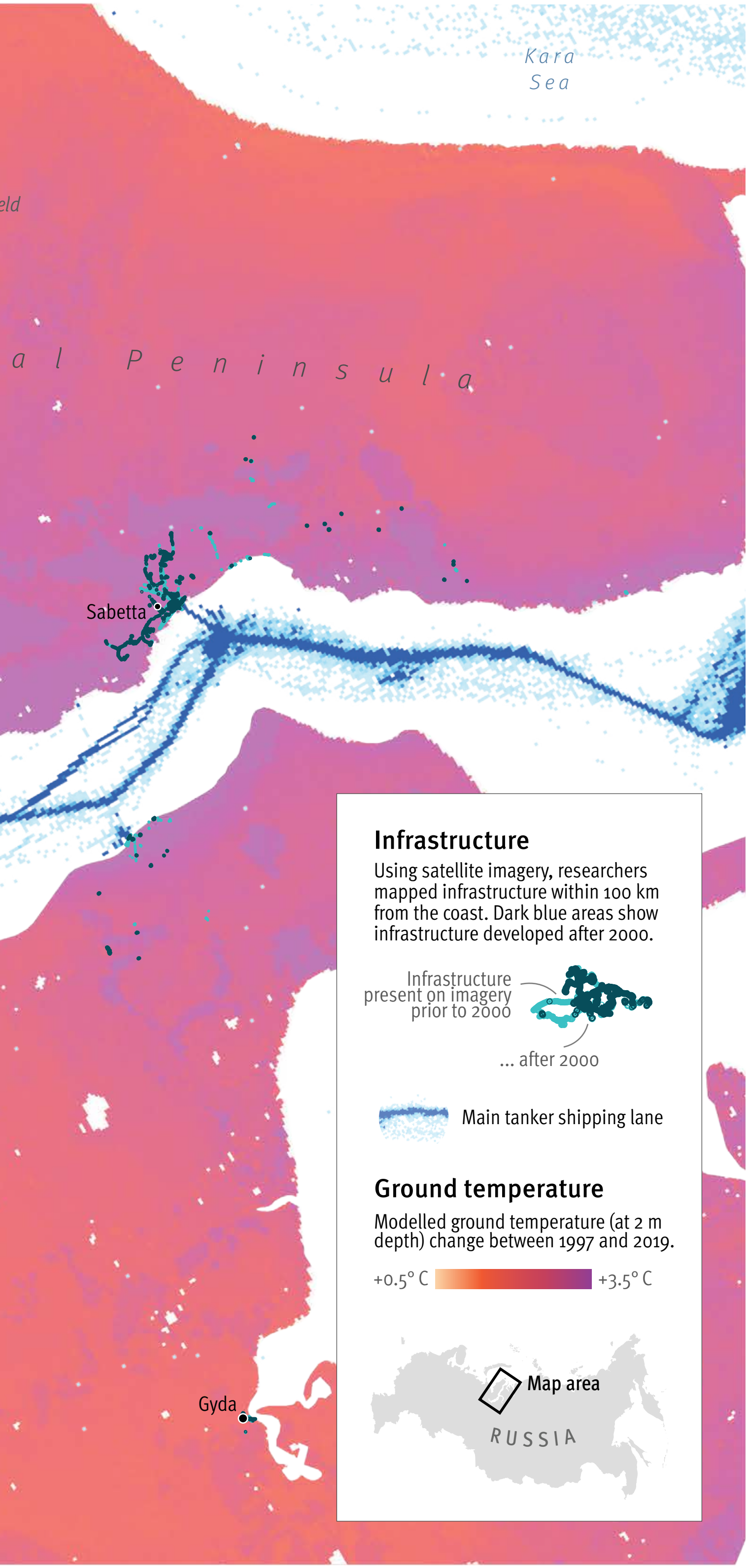
Urban infrastructure on permafrost presents numerous challenges because of the complexity of both the underlying soil conditions as well as the infrastructure above it (buildings, roads, powerlines, underground utilities, etc.). Russian city planners used one of two principles, either the passive method, i.e., maintaining permafrost in its frozen state, or accommodating thaw into the design. In some cities, however, violations of building codes took place and both principles were used in the same district. In Vorkuta, for example, plumbing and heating networks were laid underneath or close to buildings built using the passive method. These areas have experienced significant permafrost thaw and deformation of buildings.

Regardless of history, continuing permafrost thaw is detrimental to the bearing capacity of the underlying soil, which will keep causing serious problems for buildings and other infrastructure in the future. Already in north-western Siberia, permafrost thaw has reduced bearing capacity by an average of 17 per cent. By 2050, the infrastructure in the cities of Anadyr, Norilsk, Salekhard, and Yakutsk is expected to lose between 20 and 30 per cent of its bearing capacity under a high greenhouse gas emissions scenario.

In the Scandinavian countries of Finland, Norway, and Sweden, there has been far less damage to infrastructure lying on permafrost than in North America and the Russian Arctic, partly due to lower ground-ice content and less infrastructure being located on permafrost, but also as a result of higher investment and maintenance.



SOURCES: BARTSCH *ET AL.* (2021); OBU *ET AL.* (2021); PAME (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Terra infirma I

Coastal infrastructure in Yamalo-Nenets

Coastal infrastructure in the Arctic is exposed to the impacts of both permafrost thaw and increased coastal erosion that accompanies sea ice loss. Mapping of Arctic coastal infrastructure and the type of permafrost it is built on is therefore important to understand potential future impacts and provide better risk assessments.

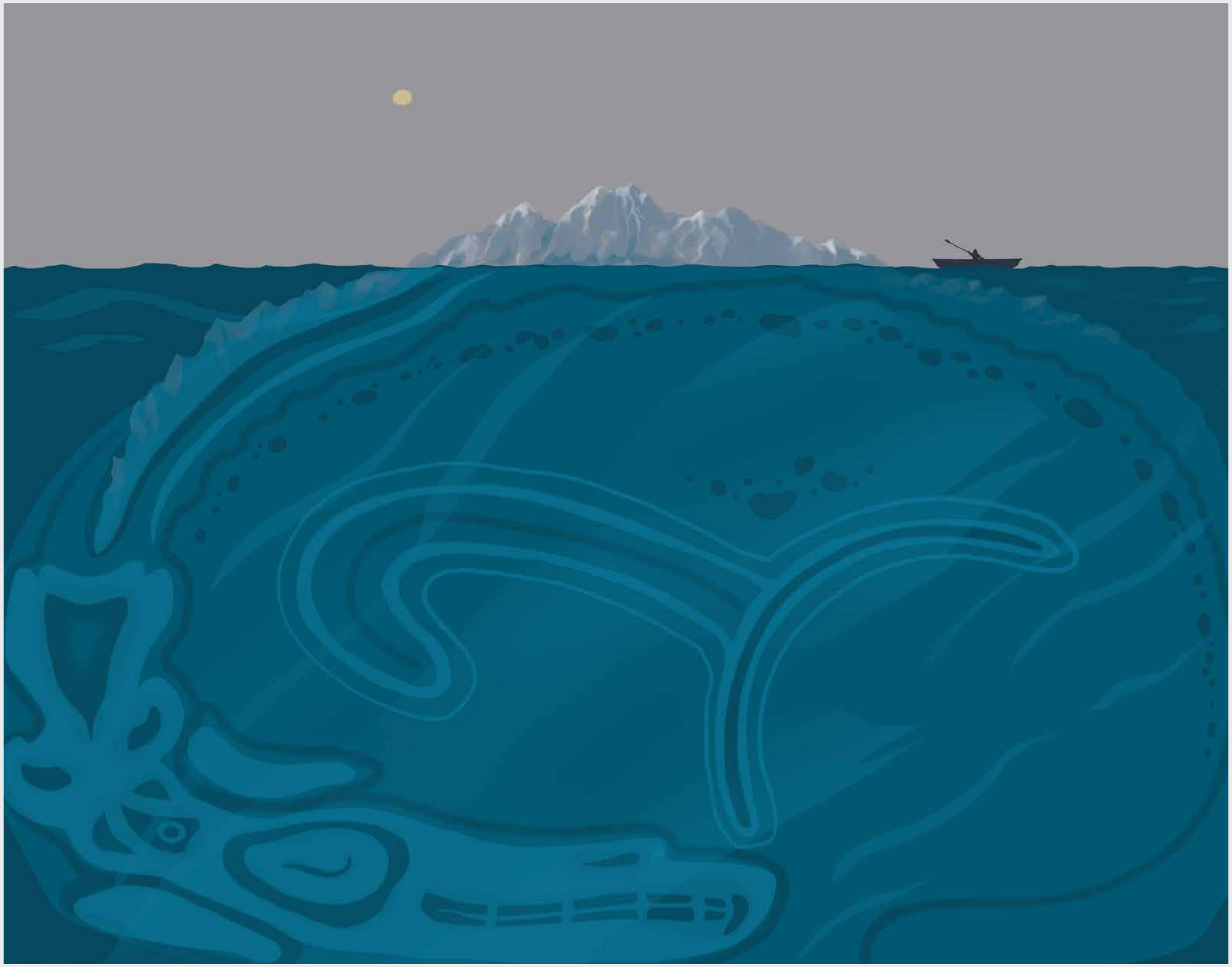
In 2021, satellite data was used for the first pan-Arctic assessment of coastal infrastructure located on continuous or discontinuous permafrost. The assessment defines coastal areas as being within 100 kilometres (km) of the coastline. High resolution data from the Copernicus Sentinel 1 and Sentinel 2 missions was combined with normalised difference vegetation index measures from Landsat imagery to identify how the human footprints in the Arctic have changed over the last two decades.

Of the approximately 6.2 million km^2 of permafrost-affected coasts in the Arctic (as defined above), about 0.02 per cent, or 1,243 km^2, are impacted by human infrastructure. Russia has by far the largest coastal infrastructure footprint on permafrost, followed by Canada and the United States. Most of this infrastructure is related to oil and gas development and mining activities. The infrastructure footprint has increased by 15 per cent since 2000, of which the majority has been in oil and gas development, highlighting the continued industrial development in coastal regions.

One of the continuously developing coastal industrial regions of the Russian Arctic is the Yamalo-Nenets Autonomous Region. As the largest natural gas province in the world, the region accounts for over 80 per cent of Russia's natural gas production and about 10 per cent of its oil. It is a region of huge importance to the Russian economy and, despite the challenges posed by building on permafrost, is home to several recently completed or ongoing industrial megaprojects. This includes the construction and expansion of the Bovanenkovo gas field and accompanying pipeline and rail infrastructure, as well as the Northern Latitudinal Railway project.

The Bovanenkovo gas field is one of the oldest gas fields in the Arctic, similar in age to Prudhoe Bay, Alaska, but where large-scale production only started in 2012. It is built on hilly terrain underlain by continuous ice-rich permafrost 140–230 metres thick and composed of wet silt and clay silt. Challenges due to permafrost thaw are well documented in this region. Included among these are landslides, which happen through a combination of rain and underlying permafrost thaw, and the melting of ground ice, resulting in water saturation and the detachment of the active layer downslope.

The Bovanenkovo gas field is also one of the most well-studied regions in the Russian Arctic for greenhouse gas emissions from permafrost. The region is known to hold intra-permafrost, metastable (relict) gas hydrates (otherwise known as hydrate-bearing permafrost). Modelling suggests that emissions of methane (a powerful greenhouse gas) from this gas field could reach between 400 and 500 thousand cubic metres over a 30-year period in the absence of heat insulation in production wells.



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PORTRAIT PHD STUDENT, UNIVERSITY OF VIENNA, AUSTRIA

Susanna Gartler

The reason why I, a central European, ended up living and working in the Arctic is because I focused on the term “subsistence” during my master studies. This led to my interest in Alaska and the Arctic in general, where subsistence is an important concept. I am living in Inuvik at the moment, at the intersection of the Inuvialuit Settlement Region and the Gwich’in First Nation traditional territories, where I’ve been conducting interviews with Indigenous land users and knowledge holders. I love the way it looks here in the beautiful Mackenzie River Delta, with all those lakes and rivers, and along the Arctic coast. Sometimes, when I go for a walk and I look around me during a sunset, I think: “Wow, this is the most beautiful thing I’ve ever seen.”

And it’s not just the land, it’s the plants and animals too. But most importantly it’s the people. I’m fascinated by the cultures, particularly the First Nation and Inuit cultures, and the way people are upholding and cherishing them. They’re really beautiful cultures and societies to me: the philosophies, the arts, the handicrafts, the governance structures, the storytelling. It’s also very interesting how the environment is storied here. I’m trying to see what the Indigenous stories and philosophies can tell us about how to live together well with all the other beings that surround us.

If you’re only looking at the land in terms of its physical properties, you’re missing a large part of why permafrost is important. Permafrost is literally the foundation of life here. It surprised me how diverse permafrost is. It is sort of a living, breathing, moving creature. During summertime when the ground broke up on the tundra, and you could see that not even half-a-metre underneath the earth there was a layer of pure ice. It blew my mind because I realised how vulnerable that is. When you realise that you and all the people around you are living on water, then you appreciate how important it is for that environment to stay cold enough.

I think part of what social science can contribute is to convey this message: that permafrost should not just be of interest because there is a lot of methane and carbon stored in it, but also because it’s the home of people who’ve lived here for millenia. As an anthropologist, I’m trained to talk to people who come from different knowledge systems, and we have an ability to bridge different social and cultural worlds. The Nunataryuk project is very interdisciplinary. We’ve had workshops where community members were involved and provided input, while also working with natural, health, and engineering scientists, who have a lot of knowledge of our different field sites.

I’m very sceptical about bringing my own agenda and imposing that on a place that I, compared with the people who lived here all their lives, barely know anything about, no matter how much I study beforehand. However, I feel like as long as my research is guided primarily by local needs, it’s a good thing. We are collaborating closely with different organisations and governments here, and we’re making sure that our findings are not just taken away and published in scientific papers, but also made available to the people that we actually develop this knowledge with. Something I’ve heard a lot of times from Indigenous elders was that we have to tackle the big challenges of our days together, a notion that really motivates me.

Terra infirma II

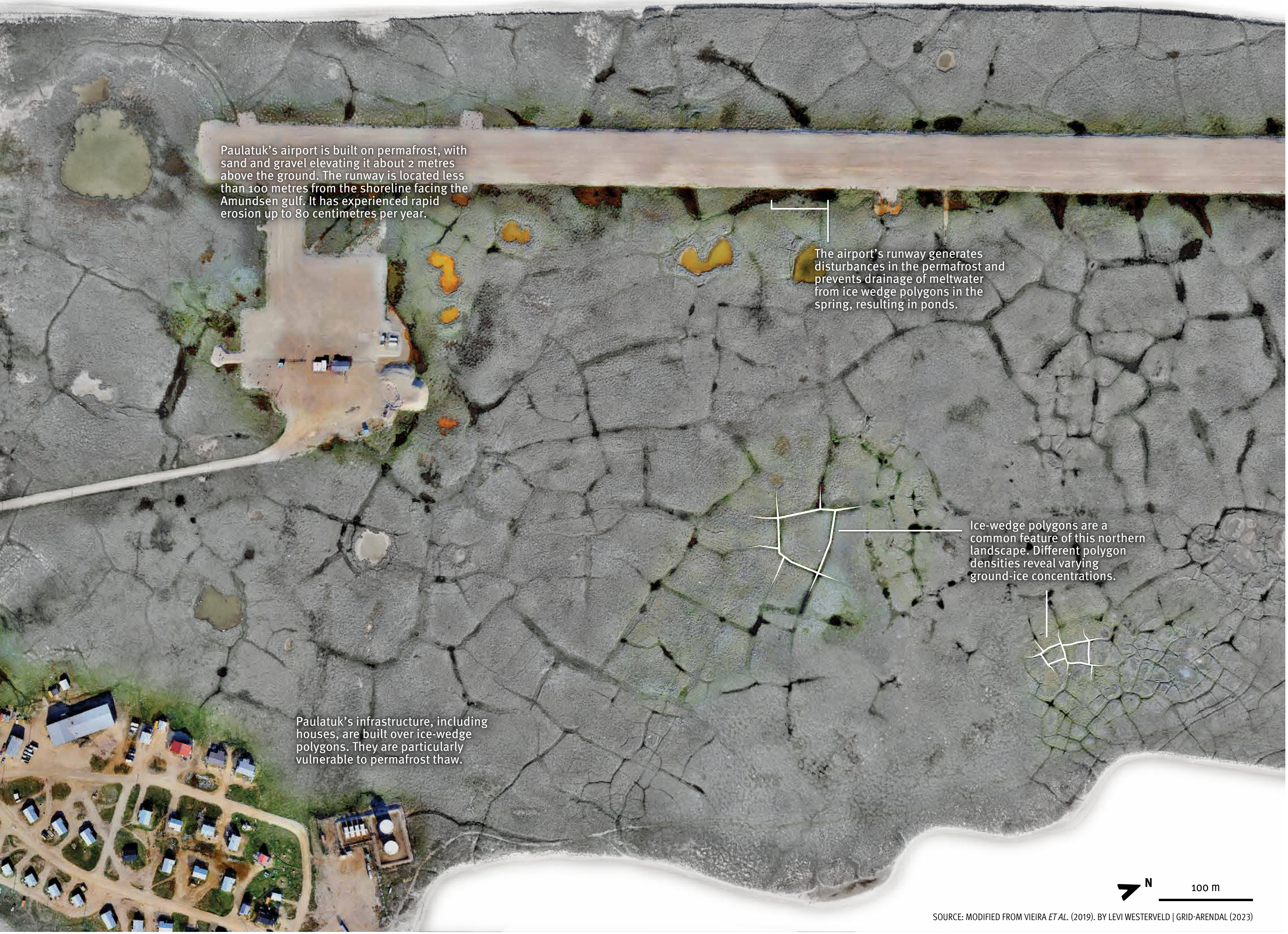
Reinforcing runways in Paulatuk

Paulatuk, a small Inuvialuit coastal settlement of about 265 people, is located on the shores of Darnley Bay in the Amundsen Gulf of the Beaufort Sea, Northwest Territories, Canada. Like many Arctic coastal communities, Paulatuk is facing impacts from coastal erosion and permafrost thaw. Located on a low-lying peninsula with an average elevation of just 3.2 metres above sea level, its western shore is experiencing rapid erosion. Between 1993 and 2020, the shoreline retreated at a rates of between 40 and 80 centimetres per year. The town is also within an area of continuous permafrost dominated by ice-wedge polygons, which are particularly vulnerable to permafrost thaw. This means that all its infrastructure, including people's homes, is at risk of damage or collapse as the warming climate causes increased erosion of the permafrost underlying the settlement.

Like so many communities in northern Canada and across the Arctic, Paulatuk is not accessible by road. Instead, it relies on air transportation and marine shipping to link both people and cargo to the rest of the country and beyond. The summer sealift, the only way to transport very large or heavy items to the community, is only available during the ice-free season in the Amundsen Gulf. This makes air transportation, which is available year-round, vital to communities like Paulatuk.

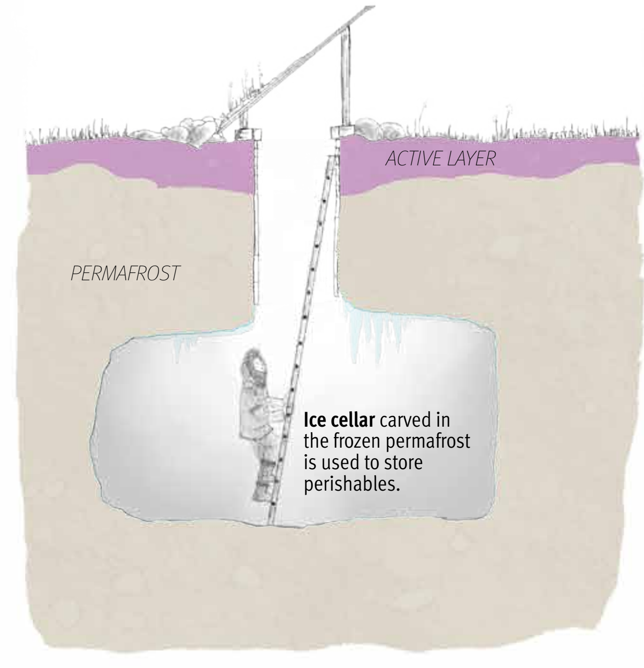
Airports are some of the Arctic's most valuable assets located on permafrost and are considered critical infrastructure for communities. Canada alone operates over 85 airports in the north, most of which have unpaved gravel runways which can become significantly weaker after periods of heavy precipitation or spring thaw.

Paulatuk's airport is situated less than 4 metres above sea level, built on ice-wedge polygons, and located 100 metres from the eroding shoreline. Subsidence caused by thawing permafrost threatens to breach the berm built to protect the runway. This could lead to flooding in an adjoining depression located at the southwestern corner of the airstrip, potentially creating problems with erosion. The airport and other infrastructure may also prevent meltwater from ice-wedge polygons from draining in the spring. The resulting ponding may damage the runway and embankments and potentially delay the refreezing of the active layer in the autumn. Furthermore, the low elevation and location of the airstrip subjects it to impacts from more intense storms, sea level rise and coastal erosion. Remote Arctic communities such as Paulatuk cannot afford to sever this critical link and need solutions to address the threats posed by climate change.



SOURCE: MODIFIED FROM VIEIRA *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Terra infirma III
Keeping cold food cold in Alaska

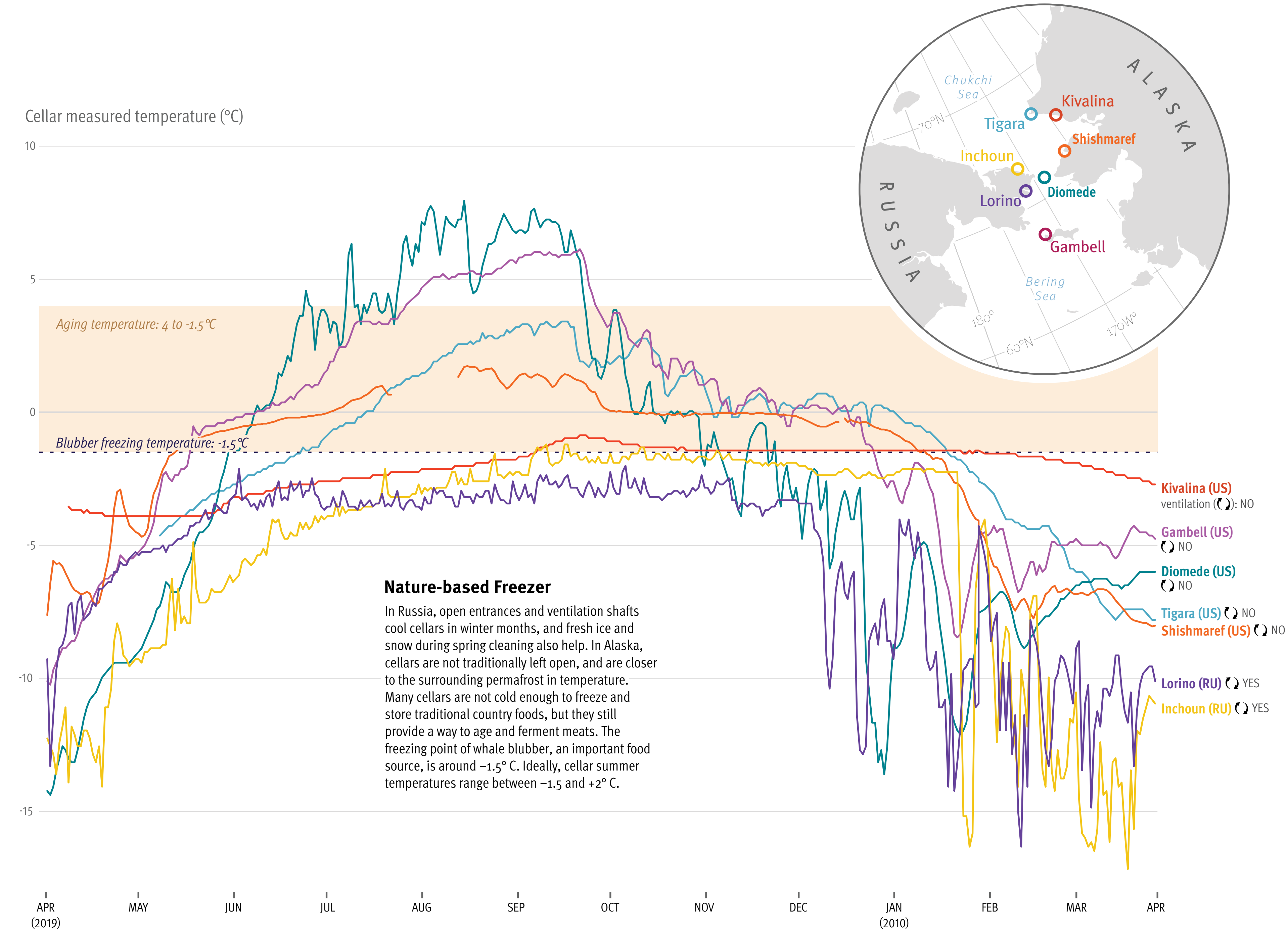


Ice cellars are a form of Arctic Indigenous technology that take advantage of the permafrost to provide natural year-round refrigeration for food. They are found in Alaska's far-north Iñupiat communities and in parts of the Canadian and Russian Arctic. As well as being a cost-effective solution to storing meat, they play an important role in Indigenous cultural identity, representing the transfer of knowledge of food preservation from one generation to the next.

Ice cellars on Alaska's North Slope come in a variety of shapes and sizes, but on average provide 10 cubic metres of space. Typically, they have a shaft 1 to 6 metres deep, ensuring that the ceiling of the cellar is well below the active layer of permafrost, are accessed through a wooden hatch or shed built over the entrance. The large size of the cellars means that not only can waterfowl, seals, and caribou be stored, but also whale meat, which requires more room for longer storage periods. While temperatures in ice cellars do not reach −18 °C as recommended by the United States Department of Agriculture for meat storage, they do allow for meat to safely age and create a particular taste that is culturally preferred.

Concerns have been raised about the future of ice cellars in Tikiġaq (Point Hope) and Utqiaġvik (formerly known as Barrow) in Alaska due to their recent degradation. At least 50 ice cellars used to exist in Tikiġaq, while today only 20 are thought to remain. A similar trend is occurring in Utqiaġvik where many ice cellars are being abandoned or considered unreliable. This decline has been attributed to various reasons, including: not being able to access the cellars safely, the presence of mould in the cellar, splintering or bowing of wood lining the cellars, water pools, seepage of briny water, the loss of sediment cohesion (sloughing), and the so-called catastrophic failure where cellars flood or collapse in on themselves.

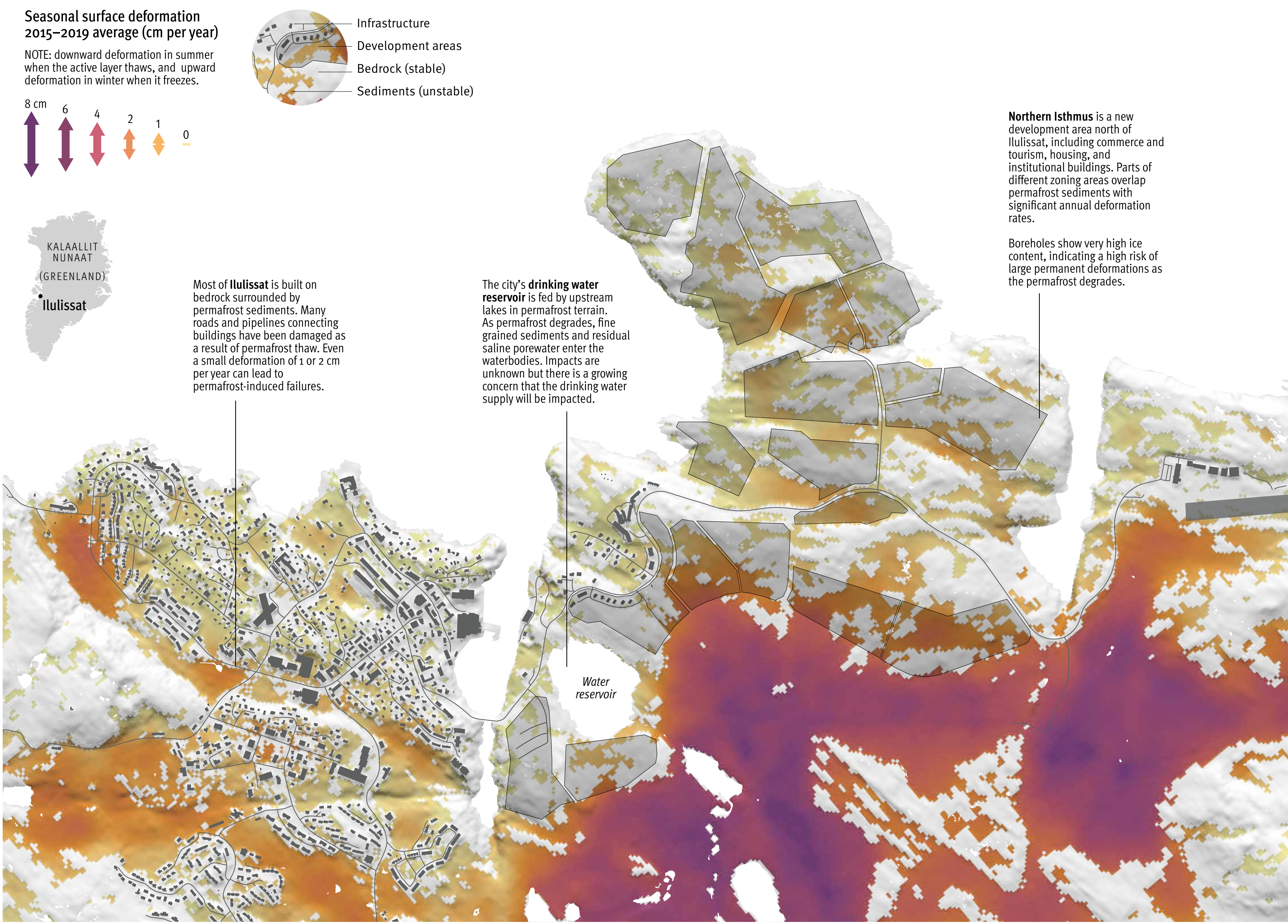
Utqiaġvik's ice cellars were the subject of a decade-long research study between 2005 and 2015. This study revealed that temperatures stayed fairly stable over the study period, with mean annual temperatures ranging from −7.8 to −6.4 °C. While warmer than the constant temperature of −11 °C reported about a century earlier, the researchers pointed to other possible contributing factors alongside permafrost thaw that could be negatively impacting ice cellars. These include local permafrost conditions, hydrological changes, irregular or poor maintenance, factors associated with urban development, and snow redistribution. Salinity is an important factor, for example, because higher salt content can lower the freezing point of water, which can decrease the ground's bearing capacity. Utqiaġvik's sediments are thought to have been deposited under marine or brackish conditions. The use of snowploughs may also affect the mechanical properties of cellars: snow is often piled on top of cellars insulating the ground and warming underground cellars, while snowbanks left over in spring can generate large amounts of meltwater that then flood cellars.



Nature-based Freezer

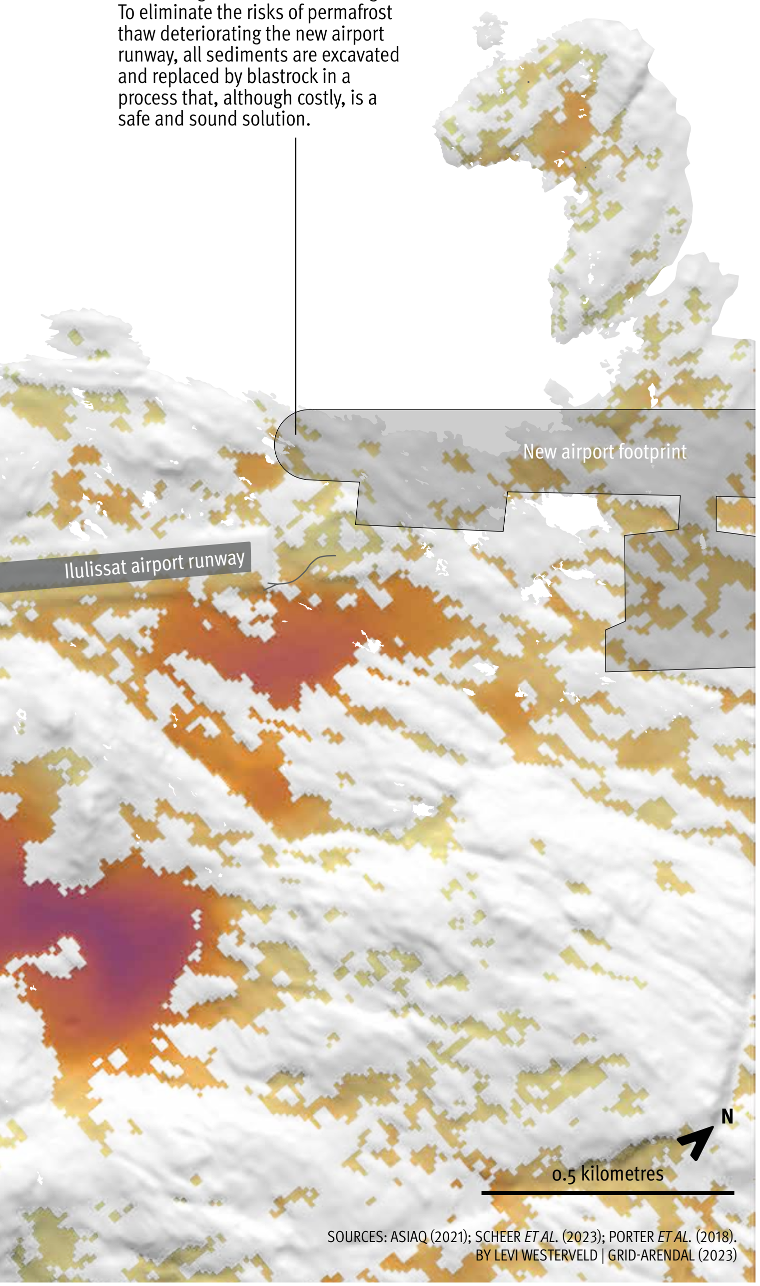
In Russia, open entrances and ventilation shafts cool cellars in winter months, and fresh ice and snow during spring cleaning also help. In Alaska, cellars are not traditionally left open, and are closer to the surrounding permafrost in temperature. Many cellars are not cold enough to freeze and store traditional country foods, but they still provide a way to age and ferment meats. The freezing point of whale blubber, an important food source, is around −1.5° C. Ideally, cellar summer temperatures range between −1.5 and +2° C.

SOURCE: YOSHIKAWA *ET AL.* (2022). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Seasonal surface deformation 2015–2019 average (cm per year)
NOTE: downward deformation in summer when the active layer thaws, and upward deformation in winter when it freezes.
8 cm
6
4
2
1
0
Infrastructure
Development areas
Bedrock (stable)
Sediments (unstable)
KALAALLIT NUNAAT (GREENLAND)
Ilulissat
Most of **Ilulissat** is built on bedrock surrounded by permafrost sediments. Many roads and pipelines connecting buildings have been damaged as a result of permafrost thaw. Even a small deformation of 1 or 2 cm per year can lead to permafrost-induced failures.
The city's **drinking water reservoir** is fed by upstream lakes in permafrost terrain. As permafrost degrades, fine grained sediments and residual saline porewater enter the waterbodies. Impacts are unknown but there is a growing concern that the drinking water supply will be impacted.
Northern Isthmus is a new development area north of Ilulissat, including commerce and tourism, housing, and institutional buildings. Parts of different zoning areas overlap permafrost sediments with significant annual deformation rates.
Boreholes show very high ice content, indicating a high risk of large permanent deformations as the permafrost degrades.
Water reservoir

Ilulissat airport's runway is relatively short, a new one is under construction and will be able to receive larger intercontinental flights. To eliminate the risks of permafrost thaw deteriorating the new airport runway, all sediments are excavated and replaced by blastrock in a process that, although costly, is a safe and sound solution.



SOURCES: ASIAQ (2021); SCHEER *ET AL.* (2023); PORTER *ET AL.* (2018).
BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Terra infirma IV

Urban planning in Ilulissat

Located on the country's west coast, Ilulissat, is the third largest town in Kalaallit Nunaat (Greenland) and a UNESCO World Heritage Site. As the top tourist destination in the country, the town is undergoing a period of expansion and economic growth. A new international airport is planned and, along with an influx of tourists, is expected to bring new business opportunities to the region. A new access road connecting the town to the airport will also encourage the development of new urban areas, including business parks and residential areas. But this planned expansion is facing some significant technical challenges related to permafrost. If not adequately accounted for, these could compromise both the new infrastructure and Ilulissat's drinking water supply.

Most communities in Kalaallit Nunaat are located on bedrock outcrops, so the main concern around permafrost relates to linear infrastructure, such as the roads and pipelines which cross sedimentary basins. Ilulissat's planned expansion will also be on bedrock, but both the airport runway (which will be 2 km long) and the roads leading to it lie on sedimentary permafrost, which is extremely ice rich in places. For the new airport, it was decided to completely excavate the permafrost sediments underneath the planned runway and replace it with other stable rock-fill material. For other linear infrastructure, however, this option is too expensive as the ice-rich permafrost can be many metres deep in places.

Permafrost sediments around Ilulissat have an extremely high ice content in the upper parts. Meanwhile, the deeper sediments, having been deposited at a time when the relative sea level was 50 metres higher than today, have a high salt content. The characteristics of Ilulissat's permafrost are such that, as it thaws, its high ice content causes the ground to subside, while the residual saline pore water brings these sediments to temperatures as low as −2 °C.

With these challenges in mind, scientists are assisting the municipality of Ilulissat in their urban planning efforts, focusing on understanding the properties of the permafrost in and around the town's sedimentary basins, particularly in terms of salinity and ice content. Several sediment cores, each with varying ice and salt contents, have been collected around Ilulissat. The sediment properties and the ice content are analysed in the laboratory and then different loads are applied to each sample to determine how thawing affects surface deformation. This allows the scientists to study how salinity, ice content, and thawing influence the mechanical characteristics of the sediment and the risk this might pose to roads and other infrastructure lying on top. Ultimately, scientists aim to develop a map and evaluation framework which can inform the municipality about the risks of construction in different areas.

Nothing in isolation

Health and wellness and permafrost

The lives of many people living in the Arctic are intimately linked with their natural environment. As climate change intensifies, a major concern becomes how the rapid environmental changes experienced in the Arctic affect both the physical and mental health and well-being of its inhabitants. Coastal erosion, decreased sea ice, weather changes, permafrost thawing on land and beneath the sea, and shifting ranges and distribution of wildlife are all happening at an unprecedented pace. This is creating new risks in terms of health and safety from bio- and geohazards such as slumps and wildfires, food and water security, and the emergence or re-emergence of contaminants and infectious diseases, including zoonoses (diseases that spread from animals to humans).

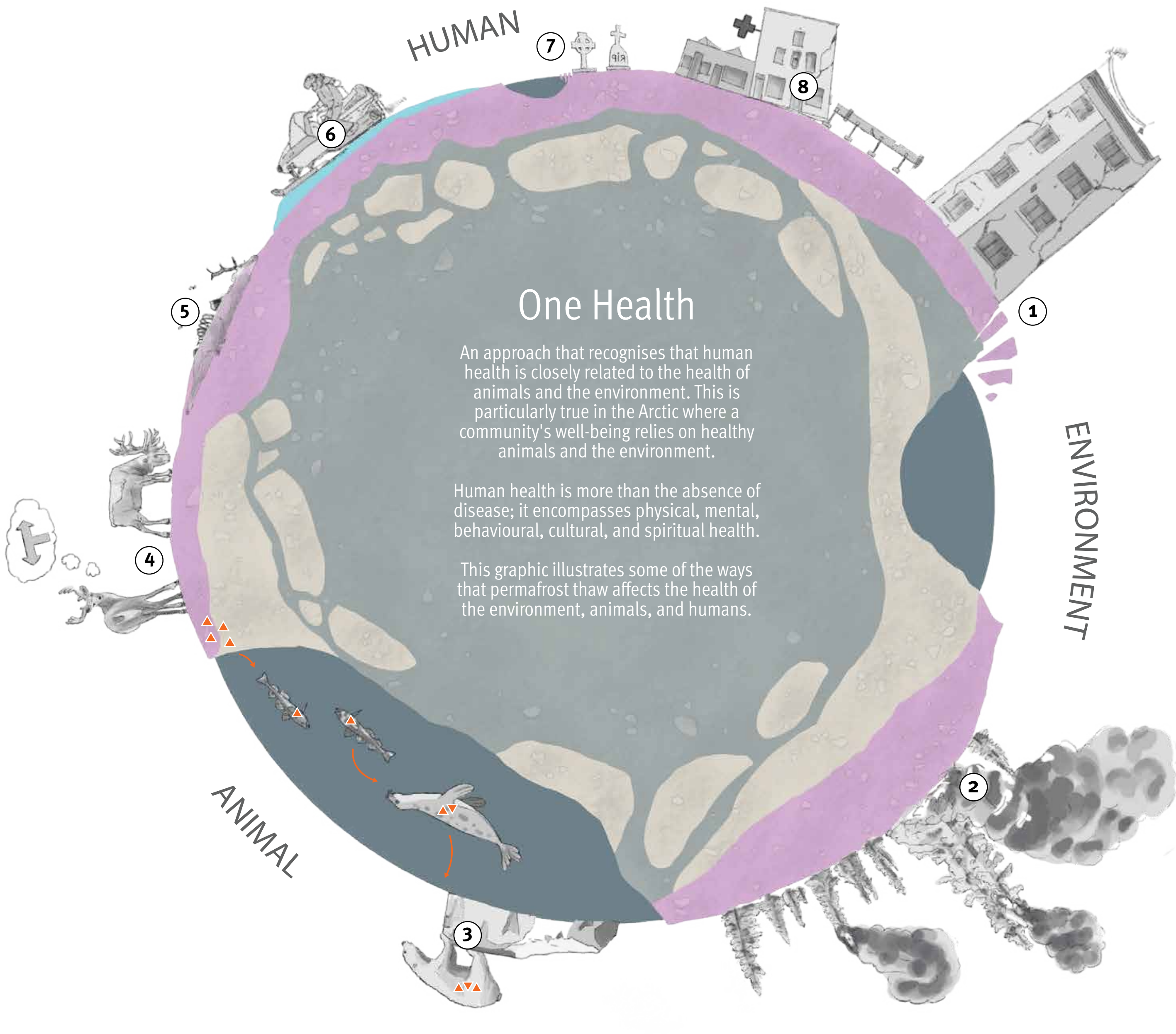
Climate change, among other challenges, is also recognised as taking a toll on the mental health, well-being, and quality of life of people. Research in the community of Rigolet, Nunatsiavut, Canada, revealed that changes in weather, snow and ice stability, and wildlife and vegetation patterns are disrupting land-based activities, damaging cultural identity and place-based solace. This has been contributing to decreased mental health and well-being, along with feelings of powerlessness and loss of control. These factors can lead to increased family stress, a greater likelihood of heightened drug and alcohol consumption, and suicidal thoughts.

Understanding the health implications of rapid environmental change in the Arctic requires a holistic approach. "One Health" recognises that human health is interconnected with environmental and animal health. It requires collaboration across various disciplines, including both natural and social sciences and knowledge systems to identify risks and to prevent and manage health risks in humans, animals, and their shared environment.

The One Health approach also recognises and seeks to include traditional and Indigenous knowledge as one form of knowledge. Indigenous communities have their own worldviews of health and well-being, which are very often grounded in the strong connection to the land and the community. In Nunavut, for example, the Inuktitut language conveys a diversity of perspectives on health, including Inuusiqatiginniq (the way of being for a person). This generally includes a holistic view of wellness that considers the surrounding environment, individual behaviours, and relationship to others.

One Health and similar approaches are now being used to understand how permafrost thaw affects human health and well-being. Permafrost degradation has several possible direct and indirect impacts on humans, animals, the environment, and the interactions between them. A study from north-western Alaska found that permafrost thaw is decreasing water and food security, leading to higher mental stress. The community of Point Hope/Tikigaq, for example, gets its water from a small tundra lake situated on top of permafrost. Higher summer temperatures, however, have led to increased algae and other biological growth, including mosquitoes, requiring water filters to be changed up to 50 times a day as opposed to the normal four in order to maintain drinking water quality. Likewise, in both Tikigaq and Kivalina, many traditional ice cellars now thaw in summer, rendering harvested bowhead and beluga meat and blubber unsafe to eat and impacting food security.

The perception of health challenges resulting from permafrost thaw vary across the Arctic. A case study from northern Canada showed that permafrost thaw creates challenges for pursuing traditional livelihoods, travelling on the land, and maintaining infrastructure. This may further impact people's self-rated health, work-life balance, and feeling of empowerment. In Kalaallit Nunaat's (Greenland) Disko Bay and on Svalbard, studies found that permafrost thaw is not perceived as a direct risk to health and mental well-being, despite the recognised impacts on culture and the built environment, and from natural hazards. People recognised the problems associated with permafrost thaw in all these areas, but still reported good well-being and quality of life. These results suggest that an awareness of challenges related to permafrost thaw supports the overall well-being. While these results were derived from a relatively limited number of participants, they could be expanded to help communities build adaptation capacity.



ENVIRONMENT:

1. Processes such as **coastal erosion, heave, and subsidence** are driven by permafrost thaw. Changes to the physical environment can be a risk to the health of both humans and animals.
2. **Water and air quality** are affected by permafrost thaw. The release of sediments and contaminants in the water due to erosion and thermokarst, as well as an increase in Arctic fires, are detrimental to the health of the environment.

ANIMALS:

3. As permafrost thaws, **contaminants (▲)** such as mercury are released and transported by rivers to the Arctic Ocean. They travel up the food chain, affecting the health of both small and large animals.
4. **Location and migration routes** of animals are changing as they adapt to changes taking place in the environment, this affects food accessibility for humans.
5. As temperatures increase, **old pathogens** may re-emerge, potentially affecting the health of both animals and humans

HUMANS:

6. Limited access to healthy animals, damaged transportation infrastructure and food storage facilities such as ice cellars, can affect **food security and human well-being.**
7. Permafrost thaw changes the **cultural landscape** of the Arctic. On riverbanks and coasts, important sites such as graveyards can be eroded and damaged due to flooding, affecting human well-being.
8. Infrastructure damage due to permafrost thaw can limit access to **safe housing, water and sanitation facilities, and other institutional and human-built infrastructure.**

BY LEVI WESTERVELD | GRID-ARENDAL (2023)

PORTRAIT EXECUTIVE DIRECTOR, QAUJIGIARTIIT HEALTH RESEARCH CENTRE, IQALUIT, NUNAVUT CANADA

Gwen Healey Akearok

I was born and raised in Iqaluit, the capital of Nunavut on the southern coast of Baffin Island, just south of the Arctic Circle. I am an epidemiologist, community health researcher, and founder of the Qaujigiartiit Health Research Centre. Through my work, I seek to answer pressing health and well-being concerns of my community.

I would describe my work at the research centre as heart-centred and relational. We work very holistically, for example by ensuring access to food that keeps us healthy, access to shelters that keep us safe from the weather and cold, and access to healthy animals that we harvest. These are all interconnected. We nurture these relationships in a way that promotes health in all these areas. I work jointly with all members of the community including elders, students, and government officials.

People outside the community, including the media, often think that mental health and high suicide rates are some of the main issues of northern communities. But they rarely look into the determinants of the mental health challenges, such as trauma history and the generation of parents, grandparents, and great-grandparents being sent to residential schools. Building on the relationship between community members and the land and reconnecting people with language and culture has helped community members heal and move down a path to overcoming traumatic events. Now, changes in the landscape due to climate change, especially changes in the migration of different animals, for example, is a source of additional stress. People talk about those concerns, the health of animals, the ability to harvest. If you can't go out and have a relationship with the land and water, that can have a significant impact on the mental well-being of our communities.

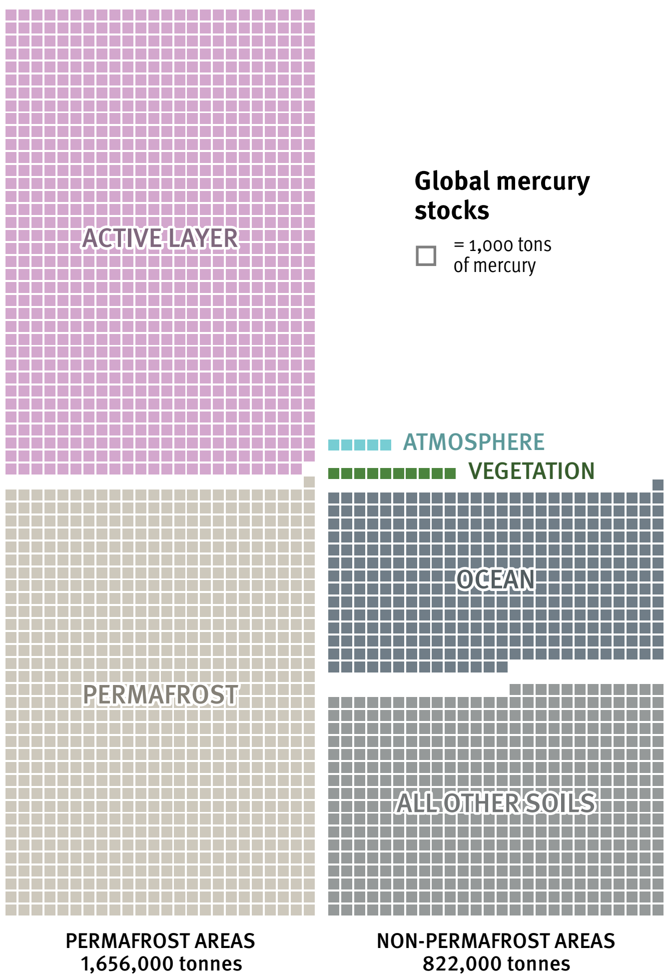
On permafrost, damage to infrastructure is one of the most important public health risks associated with thawing ground. Unpredictable swings in weather that are undoubtedly climate change-related cannot be handled by our infrastructure. Our buildings are built on steel piles right into the bedrock and permafrost. When there's heavy rain, the water and thawing permafrost, for example, causes the buildings to shift, which can lead to the collapse of structures. If our houses, our grocery stores, and all these things we rely on for shelter and food won't stand up, it's a public safety concern – which people don't usually consider.

I am also a mother, and when thinking about future generations it is hard not to think about my own childhood. We could crawl around caribou in the tundra, you could go on a walk and run into one. But now my children have never seen a caribou. It's hard not to think about all the other things that will change by the time they become adults. As a parent, you want to protect them from everything, but everything in our communities is changing so quickly, that it's hard to imagine what they might encounter. I remain positive about the future, however, thanks in part to the innovative energy of my community, but also to the increased access to knowledge and modes of communication. All of our communities have access to the Internet and cell phone coverage, so accessing knowledge from other people and information is a huge asset. I have no doubt the future generation will be even more creative when they are adults, nurturing connections across the Arctic that will help to move things forward for the good of everyone.

Toxic grounds

Contaminants and environmental health

Environmental contaminants are chemical substances released by human activities that may adversely affect living organisms, including humans. Environmental contaminants found in the Arctic include heavy metals, radioactive compounds, black carbon (soot from fires, shipping, or industrial activity), plastics (including microplastics), and other synthetic chemicals (including persistent organic pollutants such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), and dioxins). These chemicals remain stable in the environment for a long time and can bioaccumulate in the food chain, posing a danger to wildlife and human health. Many contaminants originate from more populated areas and industrial activities further south. The contaminants are carried north via air, rivers, and ocean currents and are deposited across the Arctic where they are locked in surface sediments, fresh water, seawater, sea ice, glaciers, and permafrost.



SOURCE: SCHUSTER *ET AL.* (2018). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

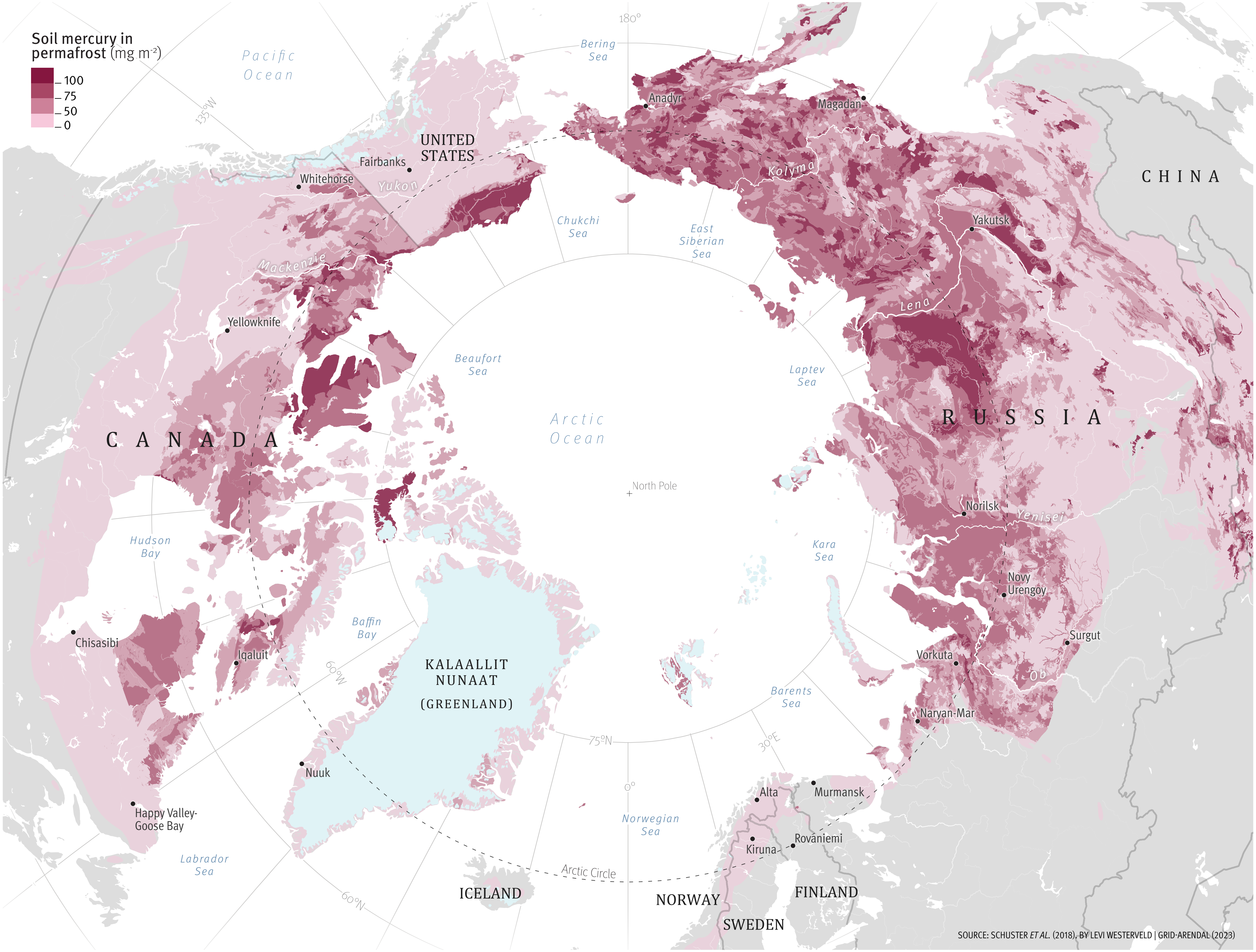
Localised sources of contaminants are also important in some areas of the Arctic, especially in and around industrial sites such as mines and other heavy industries. Environmental contaminants from these operations may include drilling and mining remains, drilling muds and fluids, mining heaps, heavy metals, spilled fuels, and radioactive waste. As the human footprint in the Arctic grows, both local and long-distance sources of contaminants are expected to increase, including chemicals of emerging Arctic concern, such as fluorinated surface protectants (PFAS) and current use pesticides.

The changes occurring in Arctic snow, ice, and permafrost raise a serious question about whether these contaminants, deposited over decades, may be released again into the environment. One of the main issues relating to thawing permafrost is the remobilisation of previously deposited contaminants. Contaminants of special concern include persistent organic pollutants such as pesticides (e.g., DDT) and industrial chemicals such as PCBs, flame retardants, or fluorinated surface protectants (PFAS).

Mercury, a naturally-occurring toxic compound, is another source of concern. Human activities have altered the global mercury cycle and released large quantities into the air, land, and water. Research suggests that permafrost is a very large reservoir for mercury compared with other soils, the ocean, and the atmosphere. However, there is a great deal of uncertainty over how much it actually contains. Regardless, it remains widely accepted that permafrost degradation could have major implications for mercury redistribution worldwide.

As permafrost thaw puts Arctic infrastructure at risk, there is also a concern about increasing environmental contamination from industrial accidents. A recent estimate suggests that more than 10,000 contaminated sites exist on permafrost in the Arctic. Future projections of permafrost dynamics indicate that up to one-third of those sites may be exposed to permafrost degradation between 2050 and 2100, which can both affect the stability of industrial infrastructure and remobilise contaminants. How changing permafrost conditions will affect each individual site, however, depends on the conditions of where it is situated. For example, waste disposal sites in some locations are now selected with greater care and the ground materials at the disposal site may be less vulnerable to the impacts of permafrost thaw.

Most remote Arctic communities have limited waste management facilities and depend on dumpsites with open burning or on sewage lagoons. If the permafrost beneath these sites thaws, it may no longer provide a barrier between adjacent soils, groundwater aquifers, and water sources.



Soil mercury in permafrost (mg m-2)
100
75
50
0
Pacific Ocean
135°W
180°
Bering Sea
Anadyr
Magadan
UNITED STATES
Fairbanks
Whitehorse
Yukon
Kolyma
CHINA
Chukchi Sea
East Siberian Sea
Yakutsk
Mackenzie
Lena
Yellowknife
Beaufort Sea
Laptev Sea
Arctic Ocean
RUSSIA
CANADA
North Pole
Norilsk
Yenisei
Hudson Bay
Kara Sea
Novy Urengoy
Baffin Bay
Chisasibi
Iqaluit
60°W
KALAALLIT NUNAAT (GREENLAND)
Surgut
Vorkuta
Ob
Barents Sea
Naryan-Mar
75°N
30°E
Nuuk
0°
Alta
Murmansk
Happy Valley-Goose Bay
Norwegian Sea
Kiruna
Rovaniemi
Labrador Sea
Arctic Circle
ICELAND
NORWAY
FINLAND
SWEDEN
60°N
SOURCE: SCHUSTER ET AL. (2018), BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Coming back to life

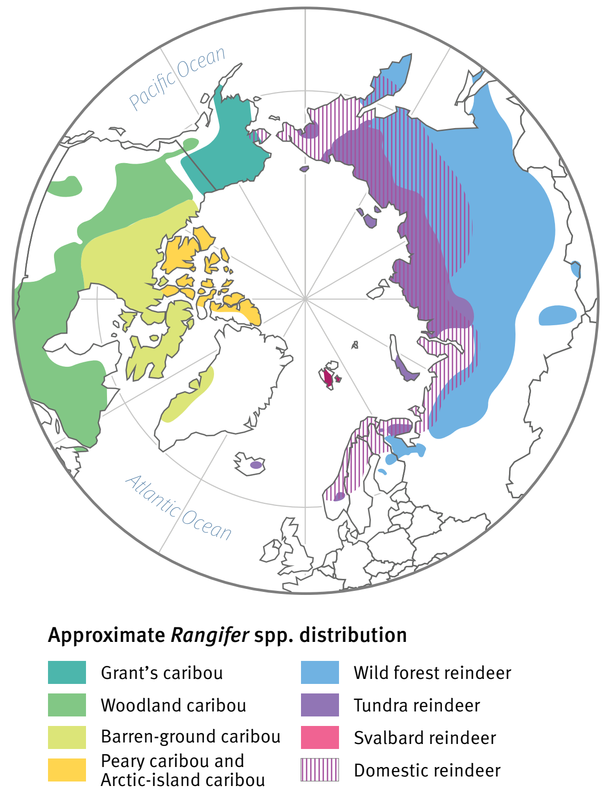
Re-emerging pathogens

Since the late nineteenth century, scientists have known that permafrost harbours pathogens, disease-causing microorganisms that include viruses, bacteria, fungi, parasites, and potentially prions. As long as permafrost remains frozen, these organisms are dormant, sometimes for thousands of years. As permafrost thaws, they can come in contact with air and water as well as animals and humans, creating conditions the pathogens need to grow and spread. The potential release of pathogens from thawing permafrost is of growing concern for human, animal, and plant health.

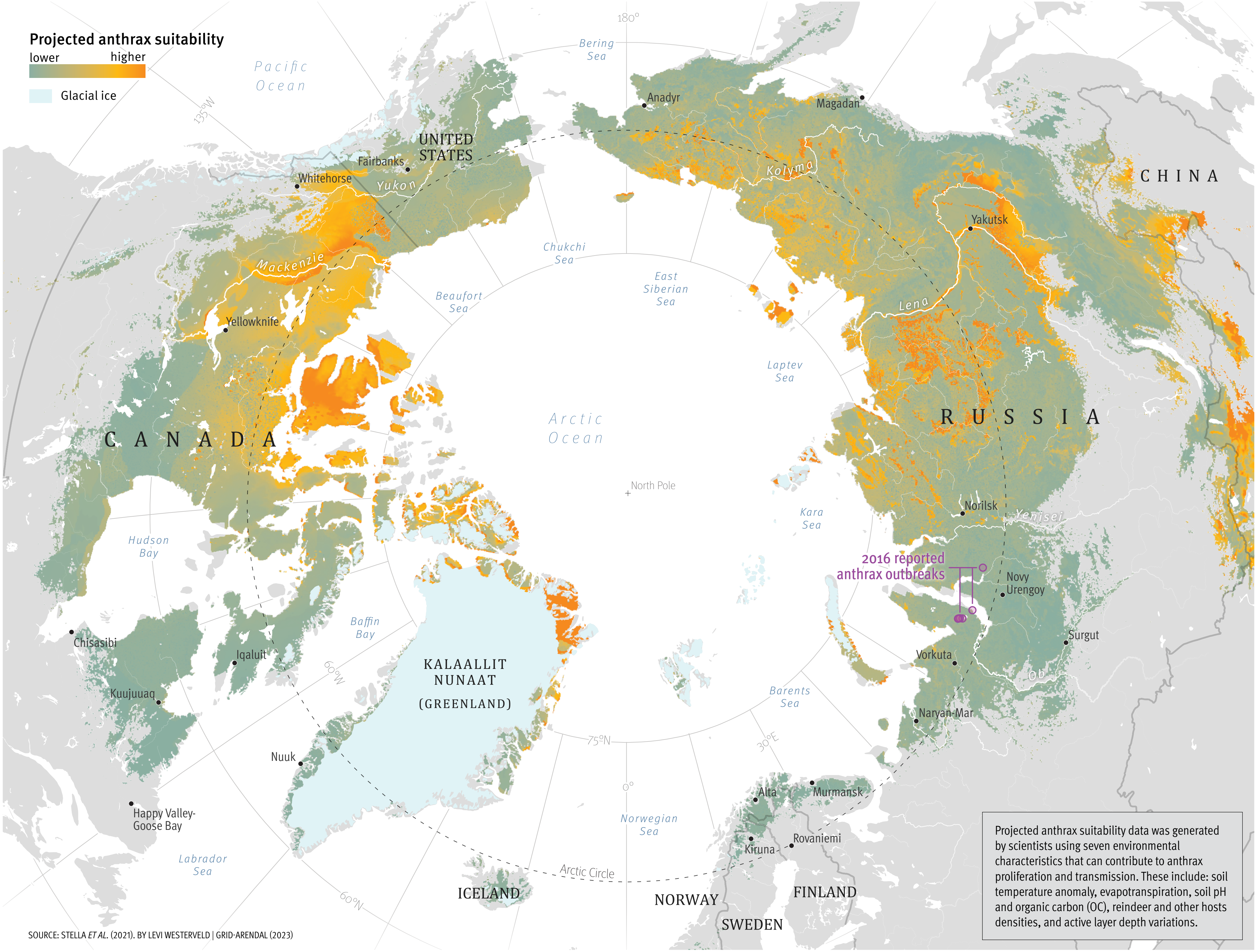
Pathogens that form endospores (dormant cells) have a high chance of survival under harsh environmental conditions and may pose the greatest risk from thawing permafrost. They include fungal pathogens, species of *Clostridium* bacteria that cause tetanus and botulism, and the anthrax-causing bacterium *Bacillus anthracis*. Anthrax, a disease which primarily affects domestic and wild-hoofed animals, was once widespread across the Russian Arctic until animal vaccines became available. Between 1897 and 1925, over 1.5 million reindeer died from anthrax, their carcasses buried in shallow graves. There are more than 13,000 of these burial grounds in Russia, over half of which are located in permafrost. A recent outbreak of anthrax on the Yamal Peninsula in 2016, which led to the death of one child, the hospitalisation of over 20 adults, and the death of several thousand reindeer, was traced back to the thawing of a 75-year-old reindeer carcass under unusually dry and warm conditions. This outbreak highlights the very serious, localised risk of anthrax to humans and animals in certain parts of the Arctic, as well as the risk to traditional livelihoods.

Permafrost thaw is also leading to rapid changes in boreal ecosystems, including changes in the composition of fungal communities, the diverse group of organisms which includes yeasts, moulds, and fungi. Pathogenic fungi originating from thawing permafrost could be potentially dangerous to human health, as well as to forestry and agriculture. For example, *Hymenoscyphus fraxineus*, a fungus originating in Asia that has devastated ash trees across Europe over a 30-year period highlights the ease with which fungal pathogens and other invasive species hitchhike on globalised trade.

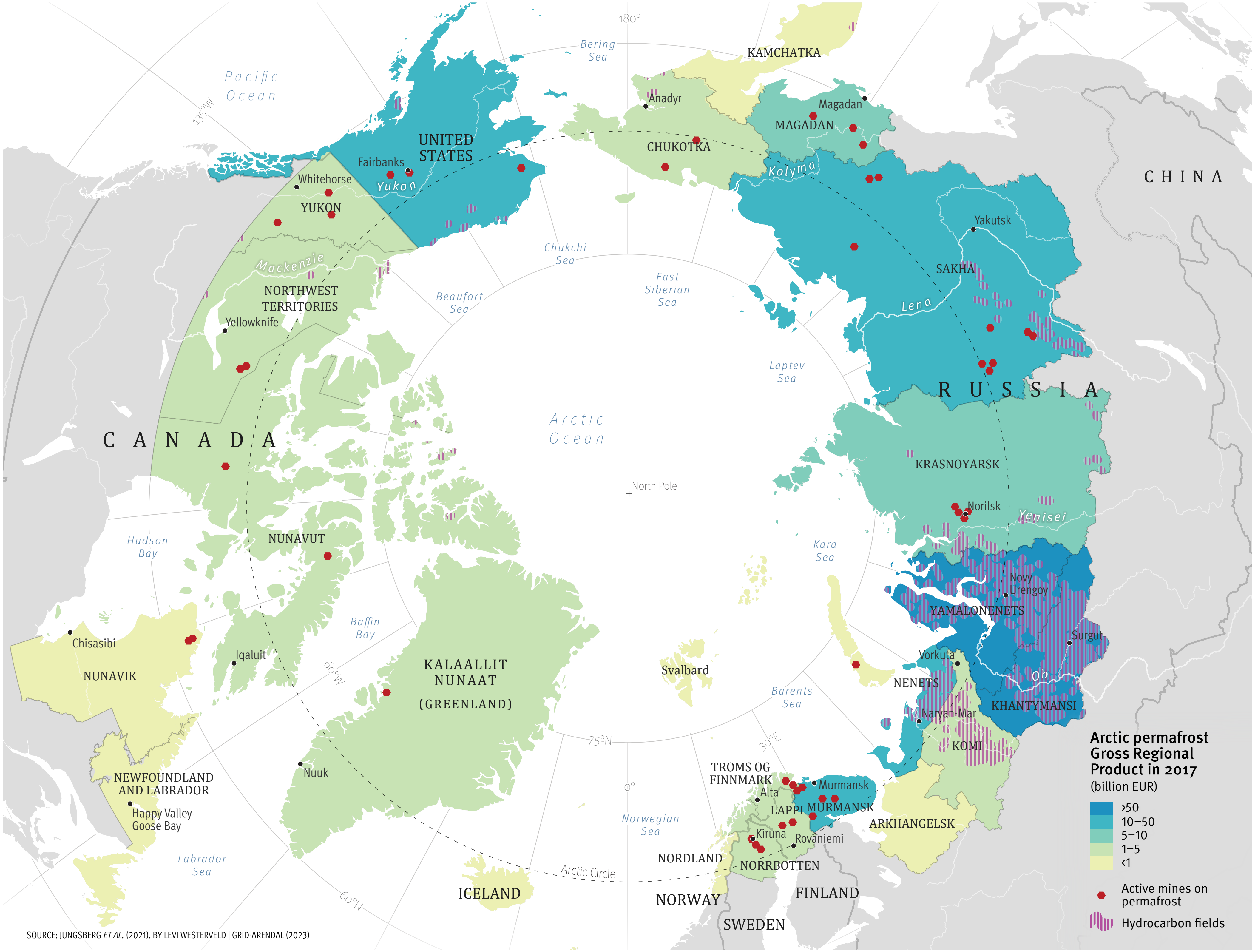
As demonstrated by the COVID-19 pandemic (caused by the severe acute respiratory syndrome coronavirus 2) and the re-emergence of the highly pathogenic avian influenza A(H5N1), RNA viruses have high mutation rates and can readily adapt to new environments, making them an increasingly important group of zoonoses (diseases that transmit between animals and humans). Within the Arctic, fragments of RNA from the 1918 Spanish influenza virus have been discovered from mass graves in the Alaskan tundra. In Siberia, fragments of DNA from the smallpox virus have been discovered in 300-year-old mummified humans. Permafrost is home to ancient "giant" DNA viruses, which could be revived under conditions of permafrost thaw, though many of these "zombie viruses" pose no threat to humans. Many scientists are now calling for more attention on and research into paleo-microbiology to better understand, predict, and plan for the resurgence of ancient infections.



SOURCE: CAFF (2001). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



Projected anthrax suitability
lower
higher
Glacial ice
Pacific Ocean
Bering Sea
180°
135°W
Anadyr
Magadan
UNITED STATES
Fairbanks
Whitehorse
Yukon
Kolyma
CHINA
Yakutsk
Mackenzie
Chukchi Sea
Beaufort Sea
East Siberian Sea
Lena
Yellowknife
Laptev Sea
Arctic Ocean
RUSSIA
CANADA
North Pole
Norilsk
Kara Sea
Yenisei
Hudson Bay
2016 reported anthrax outbreaks
Novy Urengoy
Baffin Bay
Surgut
Chisasibi
Iqaluit
60°W
KALAALLIT NUNAAT
(GREENLAND)
Vorkuta
Ob
Kuujjuaq
Barents Sea
Naryan-Mar
75°N
30°E
Nuuk
0°
Alta
Murmansk
Happy Valley-Goose Bay
Norwegian Sea
Rovaniemi
Kiruna
Labrador Sea
Arctic Circle
60°N
ICELAND
NORWAY
FINLAND
SWEDEN
Projected anthrax suitability data was generated by scientists using seven environmental characteristics that can contribute to anthrax proliferation and transmission. These include: soil temperature anomaly, evapotranspiration, soil pH and organic carbon (OC), reindeer and other hosts densities, and active layer depth variations.
SOURCE: STELLA ET AL. (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



SOURCE: JUNGSBERG *ET AL.* (2021). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Frozen assets I

The formal economy

A common feature of Arctic regions is their mix of formal and subsistence economies. The formal economy includes large-scale resource extraction, such as oil and gas, timber, fishing, and mining, all of which serve national and international markets. Local economies, on the other hand, provide goods and services to the local population, including public sector jobs. Traditional, subsistence activities, which include hunting, fishing, herding, and gathering, can also form a significant part of the local economies.

Calculating the potential economic risk and cost of permafrost thaw can be done in several ways. Standard economic indicators like GRP* can be combined with the extent and types of permafrost to understand how much economic activity is potentially at risk from permafrost thawing. The entire Arctic permafrost region is, in fact, one of the most productive economic regions on Earth. With a GRP of USD 458 billion (2017), this is equivalent to a GRP per capita of over USD 71,000, a figure that is higher than for Germany and the United States and just below the GRP per capita of Switzerland. However, the financial benefits of production are not necessarily re-invested in the region but are often transferred out so these high numbers may hide some of the poverty observed among local communities.

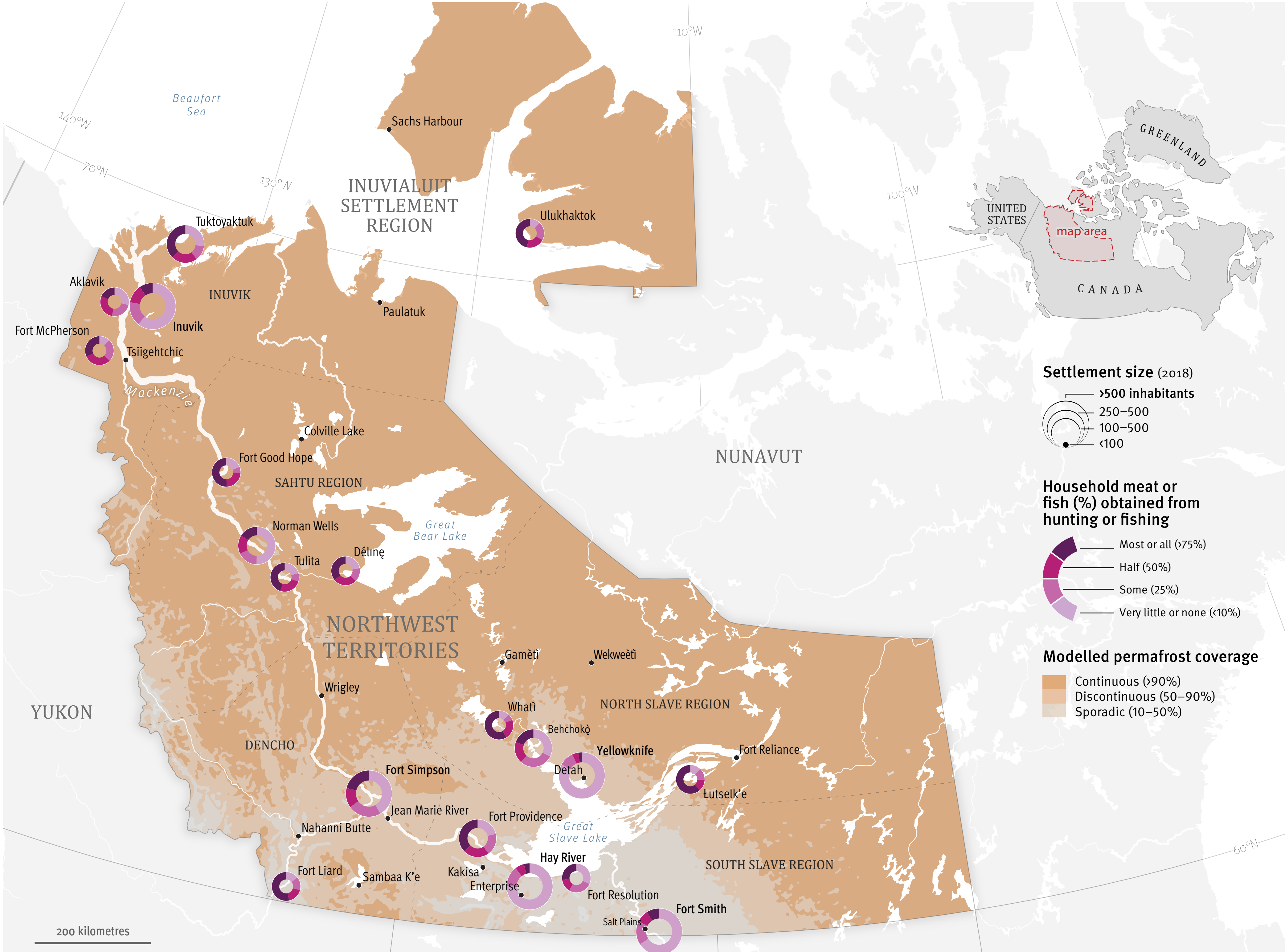
GRP per capita can also indicate the availability of economic resources to adapt to the adverse impacts of climate change. Permafrost regions with low GRP per capita possess limited resources for adaptation and are thus considered more vulnerable. The type of permafrost is also a contributing factor: economic activities situated in areas with discontinuous and continuous permafrost will experience greater change than those in sporadic and isolated patches, so that regions such as Sakha Republic and Yamalo-Nenets are considered to be the most vulnerable. GRP per capita has also been combined with other social and physical indicators to create the Arctic Permafrost Population Vulnerability Index.

*Gross Regional Product is a measure of the total value of goods and services produced in a region. When GRP is divided by the total population, a per capita value is obtained, which indicates the average income per inhabitant.

Permafrost thaw has already resulted in widespread impacts and costs on all parts of society. Settlements may have to be relocated, new housing may need to be built, existing buildings will need to be repaired to avoid collapse, while roads, railways, airports, and pipelines will need to be fixed. While calculating the economic cost of permafrost thaw in the Arctic is an emerging field of research, several estimates are available, many of which focus on the cost of maintaining, replacing, or upgrading existing infrastructure. Typically, these will explore several scenarios, including a lower or higher emissions scenario, depending on how carbon intensive the future direction of our global society will be. In certain cases, the extent to which timely adaptation measures can reduce future damages and thus costs is also calculated.

These types of estimates help to communicate the urgent need to reduce emissions, while simultaneously pointing to the need to adopt smarter adaptation choices in the near term to reduce costs in the long term. For example, the cost of maintaining Alaska's public infrastructure under a business-as-usual scenario is estimated at USD 5.5 billion by 2099 (under a high-emission scenario) or USD 4.5 billion (under a lower-emission scenario). Meanwhile, the adoption of proactive measures, mainly related to flood measures on Alaska's roads, was estimated to bring those costs down to USD 2.9 billion and USD 2.3 billion for high- and low-emission scenarios, respectively.

Moreover, the contribution of carbon and methane into the atmosphere can be calculated in terms of economic costs to global society. The global costs associated with continued permafrost thaw through the release of carbon and methane are projected to far outweigh any benefits, such as the spread of agriculture northward, underscoring the need for urgent action to stabilise emissions. In 2015, researchers estimated that continued permafrost thawing could cost the global economy USD 43 trillion by 2100 – roughly equivalent to half the annual global economic output today. Even if the world manages to stabilise temperatures well below 2 °C above pre-industrial levels, permafrost thaw, through the release of greenhouse gases is calculated to cost the global economy almost USD 25 trillion, or about 4 per cent of the total cost of climate change to the global economy.



SOURCES: NWT BUREAU OF STATISTICS (2018); OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Frozen assets II

Traditional and subsistence activities

Traditional and subsistence activities are mostly unaccounted for in official economic statistics across the Arctic (excluding Alaska), which makes such activities largely invisible in measures of income or wealth, including GRP. However, many studies of individual communities highlight the crucial importance of subsistence activities, particularly in terms of the food obtained from fishing, hunting, and foraging, also known as "country food". It is critical to understand how permafrost thaw may impact the type and abundance of country food as well as access to it.

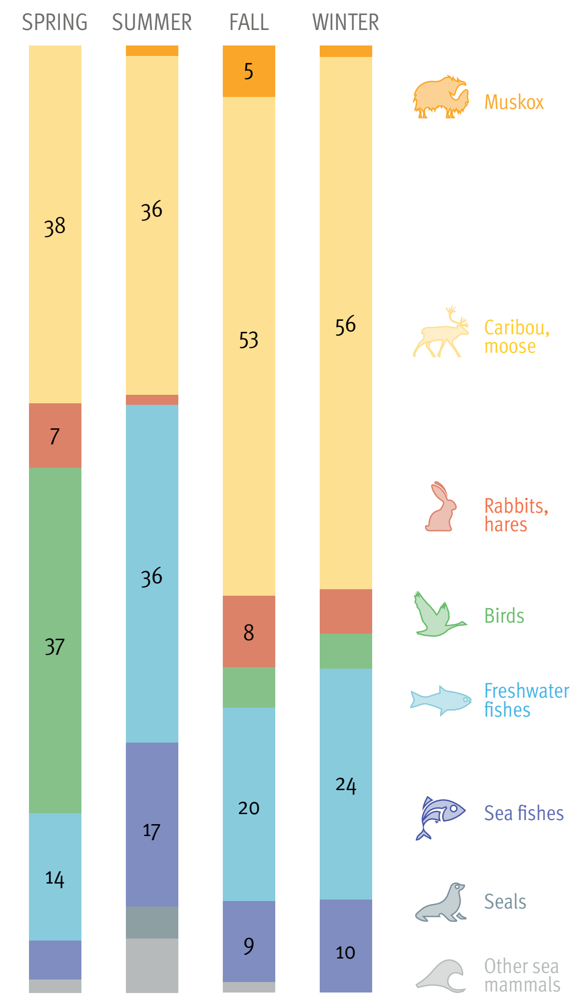
Market pricing techniques* have been used to put a monetary value on subsistence activities happening on permafrost landscapes of three coastal communities: Aklavik (Canada), Qeqertarsuaq (Kalaallit Nunaat/ Greenland) and Longyearbyen (Svalbard, Norway). Each community differs in the types of subsistence activities undertaken by its inhabitants, including the proportion of country food in their diets.

Almost 50 per cent of the food eaten in Aklavik and 60 per cent eaten in Qeqertarsuaq are obtained through hunting, gathering, trapping, and whaling, while in Longyearbyen it is only 10 per cent. Should the permafrost landscapes and the food they supply disappear, inhabitants of Aklavik and Qeqertarsuaq would have to pay EUR 240 and EUR 460, respectively, to purchase this food, which represents 43 per cent and 17 per cent of their monthly incomes per capita. While these numbers are theoretical, they highlight the real economic importance of subsistence activities and a potential cost-of-living crisis, should country foods become unavailable in the future. Store-bought foods are very expensive given the high commodity prices across the Arctic. Such high costs would severely impact purchasing power and reduce the well-being and ability of inhabitants to satisfy their basic needs.

*Market pricing techniques use market prices from a surrogate market to assess the monetary value of non-market goods and services. For example, for assessing the value of country foods, the equivalent price that it would cost to obtain that type of food from a conventional market (shops, stores, or supermarkets) is used.

The way in which Arctic ecosystems and plant and animal communities will respond to thawing permafrost is an emerging field of research and it is relatively unknown how these changes will affect subsistence activities. Changes in soil temperature, moisture, and nutrients are likely to alter plant composition. Where ground-ice content is high, subsidence of the landscape may lead to the formation of ponds and lakes, shifting a terrestrial habitat to an aquatic one. Changes in the vegetation and landscape may lead to altered animal migration routes or changes in animal species composition, and influence humans' access to country foods. For example, hunting may take longer if hunters need to go around thaw slumps, or because moose hide better behind taller willows. As the climate warms, some Arctic species may be displaced by others better adapted to the new conditions. On land, changes in ground conditions could lead to a change in hunting routes or reduced snowmobile access. It is during this "transition phase" when human societies are adapting to the changes that the costs may be greatest.

Proportion (%) of the most-consumed species in Aklavik, CA.



SOURCE: RAMAGE *ET AL.* (2022). BY GRID-ARENDAL (2023)

Cultural homeland

Alaas landscapes in Yakutia

Situated in the Russian Far East, the Republic of Sakha (Yakutia) is a unique permafrost region. The Central Yakutia lowlands, which extend along the middle basin of the Lena River, are characterised by ice-rich permafrost which can be several hundred metres deep. A key feature of this region are the alaas permafrost landscapes, which consist of thermokarst depressions or drained thaw lakes with large areas of subsided ground surface. Over 16,000 alaas exist in Central Yakutia covering an area of 4,400 km^2.

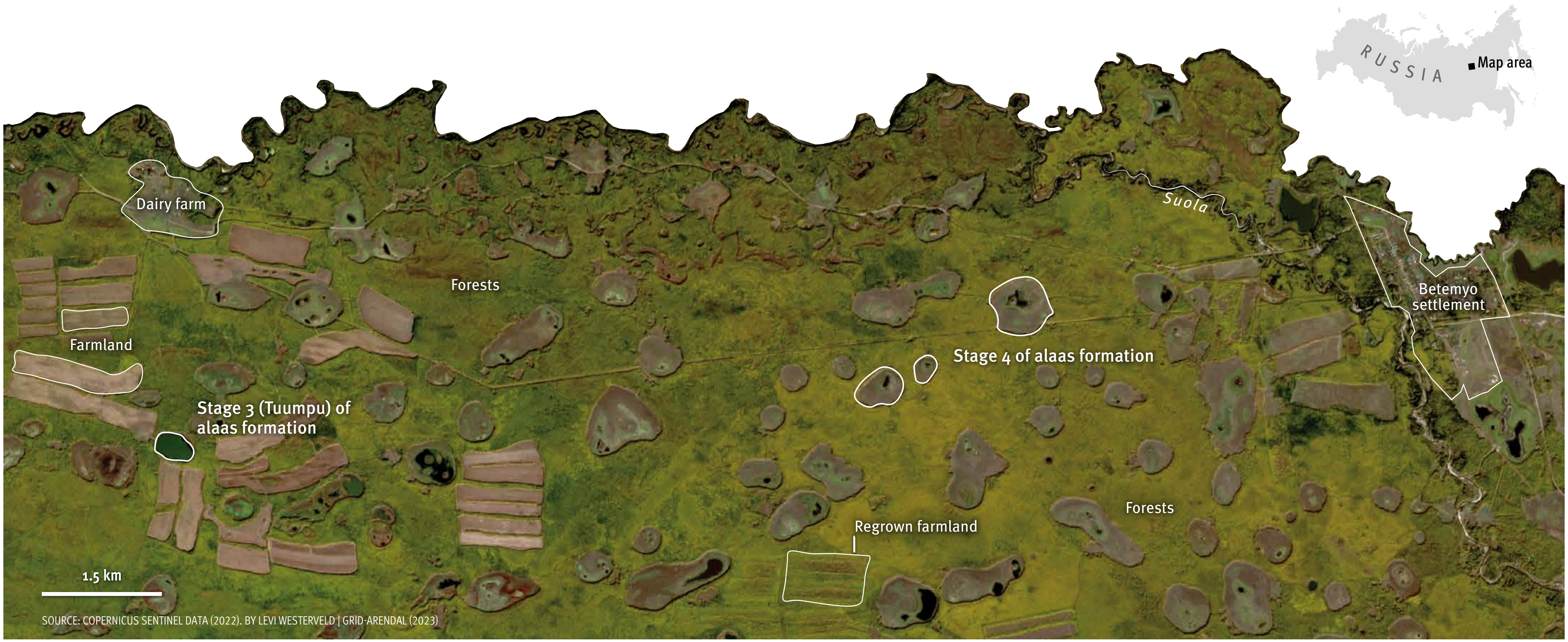
In the Sakha language, "alaas" means "a field or meadow, surrounded by forest; a piedmont valley".

Sakha people depend upon alaas and consider it their homeland, imbued with spiritual qualities in accordance with their animistic beliefs. Later, as land development demanded the scientific study of alaas ("alas" in English and Russian) to build and exploit resources, the definition became highly technical: a landform distinguished by large areas of subsided ground surface resulting from the thawing of ice-rich permafrost.

The formation of alaas can take anywhere from decades to hundreds of years. The process starts when the area becomes naturally deforested, followed by deepening subsidence and ice-wedge degradation.

As the ice wedges thaw, the depression is filled with meltwater and becomes a lake. In the final stage, the landscape dries out and grassland is formed on the middle and outer edges of the depression.

Alaas grassland areas have attracted and sustained animal husbandry for at least 500 years, forming the basis for the thriving communities and culture of the Sakha people. Between the twelfth and fifteenth centuries, the region's Turkic ancestors migrated north from the Lake Baikal region and settled around the alaas within the Lena and Viliui River basins. Using practices carried over from their southern ancestors,



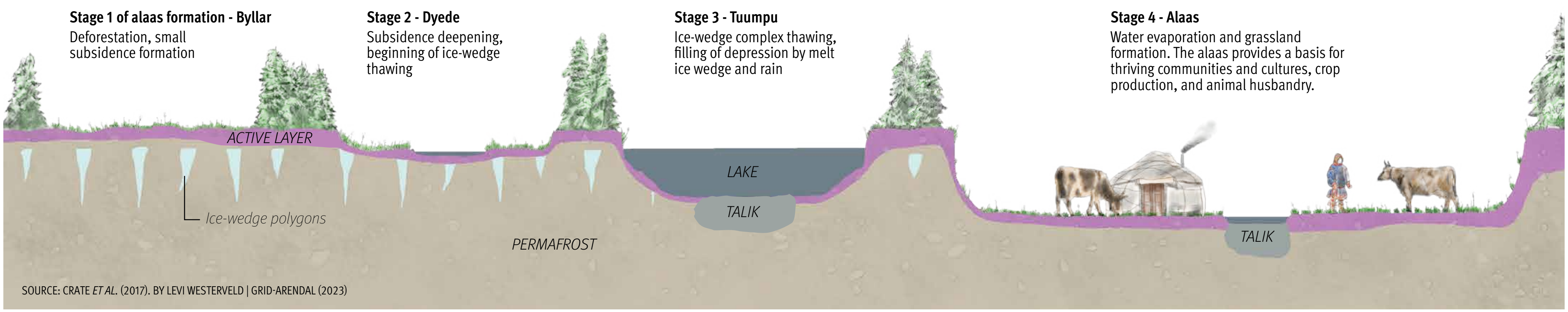
SOURCE: COPERNICUS SENTINEL DATA (2022). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Sakha successfully manipulated the alaas landscapes to maximise hay production for their cattle and horses. They drained waterlogged fields during wet years and created a system of canals and dams to hold water in times of drought. They also created more pasture and haylands by draining lakes and removing forests by burning. Alaas are considered sentient beings according to Sakha's historic beliefs. Sacrificial foods as well as rituals and blessings are offered to the alaas. Extended clans consisting of groups of five to 15 households would live on the alaas, migrating between summer and winter camps.

Starting from the seventeenth century and coinciding with the introduction of Russia's land tenure taxation system, cattle surpassed horses in importance, and the alaas were primarily managed to produce hay as fodder for cattle. The Soviet period, starting in the 1920s, brought the collectivisation of farms and the formation of compact villages. The alaas began to be used for large-scale crop production, pasture, or fodder. From the 1960s onwards, there was a shift from using native Sakha cattle to European breeds. Not able to withstand the harsh winters, the European breeds needed to remain indoors for 9 months of the year and fed fodder. The result of this was an intensification of hay farming and mass drainage of the alaas to create more grassland. The collapse of the Soviet Union brought further changes: state farms were disbanded and large-scale cattle breeding was no longer profitable. Most households adapted, however, by holding a few cattle for their subsistence. Many of the grasslands, which were converted to croplands during the Soviet period, were converted back to natural hayfields.

Like other landscape features, alaas are not immune to the ongoing changes in permafrost. Many thermokarst lakes are expanding in size and volume with increased summer precipitation, above average snow cover, and increased permafrost ice meltwater as the principal causes. Alaas have also seen changes in their flood regimes. Typically, they only flood during the spring due to melting ice and snow, but now summer floods have become more common. While spring floods bring nutrients and are considered beneficial, summer floods make hay production impossible. Waterlogging of alaas not only limits hay production, but limits access to forests and other resources. For some households, relocation is needed due to the increasingly damp conditions.

The ongoing use of alaas is dictated not only by environmental conditions, but also by social and demographic trends and consumption patterns. Due to a combination of factors including a lack of fodder from the land, youth outmigration to Yakutsk, and a shortage of workers, some inhabitants have abandoned cattle breeding. Instead, many are now opting for horse breeding, which generally involves less work. Horses also carry more prestige in post-Soviet Sakha culture.

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Holding Tight

Adaptation to Permafrost Thaw

Bumpy road ahead

Transportation infrastructure and permafrost

A wide array of transportation technologies are used to move people and goods into, out of, and around the Arctic. These range from raised wooden paths over muddy ground to elevated utilidors* above frozen ground, from year-round highways to seasonal ice roads, and from marine ports to airports which provide some communities their only link to the rest of the world. To some degree, permafrost degradation will affect most of these transportation technologies, if not all.

There are two primary drivers of ground thermal changes and thawing around transportation infrastructure: increasing temperatures caused by climate change and direct impacts from infrastructure itself (e.g., localised heating of the ground and disruption of insulating vegetation). Combined, these effects double the pressure on permafrost, stressing transportation infrastructure as well as Arctic lives and livelihoods.

*A utilidor is a utility corridor or tunnel used to transport electricity, water, and sewage. In permafrost regions, insulated utilidors are placed above ground to prevent permafrost thawing and decrease the risk of infrastructural damage.

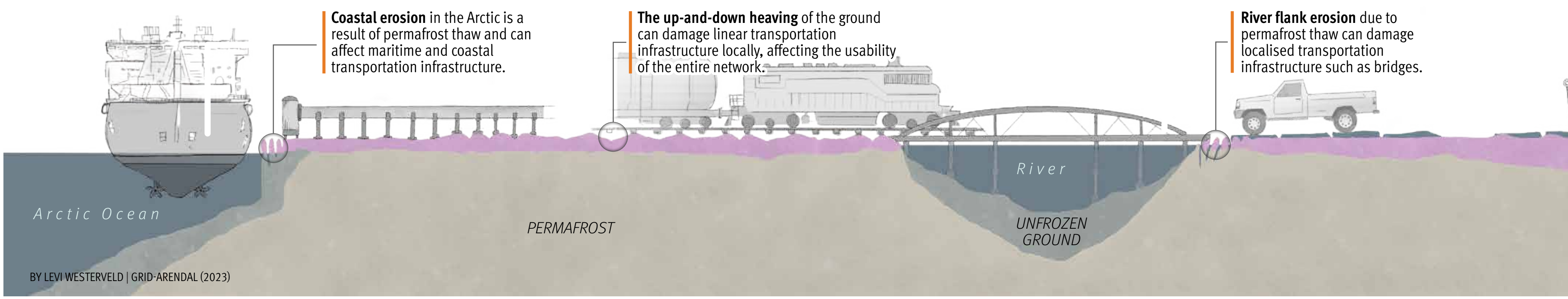
Changes in adjacent permafrost terrain is also a threat in many places, particularly thermokarst features. When permafrost thaws, ground ice melts leaving behind depressions in the landscape. These fill with meltwater to form ponds or larger thermokarst lakes. These depressions expand during summer when air temperatures are higher, which fragments the landscape. Expanding thermokarst features threatens foundations of transportation infrastructure as it weakens the sediment strength, and, in some cases, even leads to total collapse.

Both point infrastructure (e.g., ports and airports) and linear infrastructure (e.g., roads and pipelines) are vulnerable to permafrost thaw. Infrastructure development in coastal areas has been growing rapidly in recent decades, and much is built on ground which will be affected by thawing permafrost. This infrastructure is often used for the transportation and export of natural resources. Damage caused by a reduction in the ground's bearing capacity as the permafrost deteriorates poses a risk for current and future economic development. At airports, distortions created by permafrost thaw are negatively impacting the integrity of runways, causing safety concerns and potentially paralysing this type of transportation.

Linear infrastructure is vulnerable to permafrost thaw as changes in the heterogeneous ground cause differential settlement and distort the structure. One weak point along linear infrastructure can make the whole network unusable (for example, a break in a pipeline). The length of infrastructure and the weak points along its route are therefore important factors to consider when assessing overall vulnerability.

Transportation in the Arctic is multimodal, meaning that different transportation technologies are interlinked in a network to move people and goods between places. For a multimodal network to function, it requires the integrity of all the different infrastructural components. A defective runway or road may have negative impacts across the network. Almost 30% of roads located in Arctic permafrost regions are considered at risk of ground subsidence under moderate greenhouse gas emissions scenarios, rising to 44% under high emissions scenarios. Among these, the largest number of roads at risk is in Russia, where the estimated average costs for replacement range from about USD 50 to USD 70 million, depending on the scenario.

Multimodal transportation infrastructure and impacts of permafrost degradation

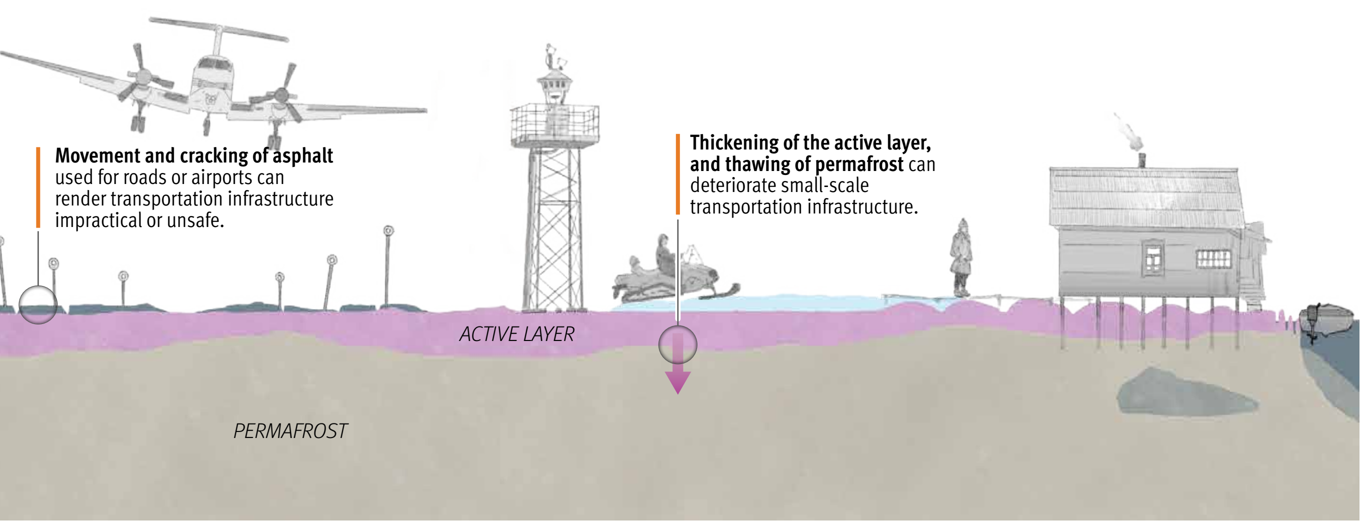


Since the 1960s, greater efforts have been made to understand the physical impacts of climate change on transportation infrastructure and to adapt construction and maintenance to those changes. Improved risk assessments of existing and planned infrastructure projects can help better manage impacts from permafrost thaw. For example, integrating high-level details from geotechnical models with large-scale, long-term land surface models may better project the combined impacts from climate warming, infrastructure development, and permafrost degradation in order to adapt to both slow and rapid changes.

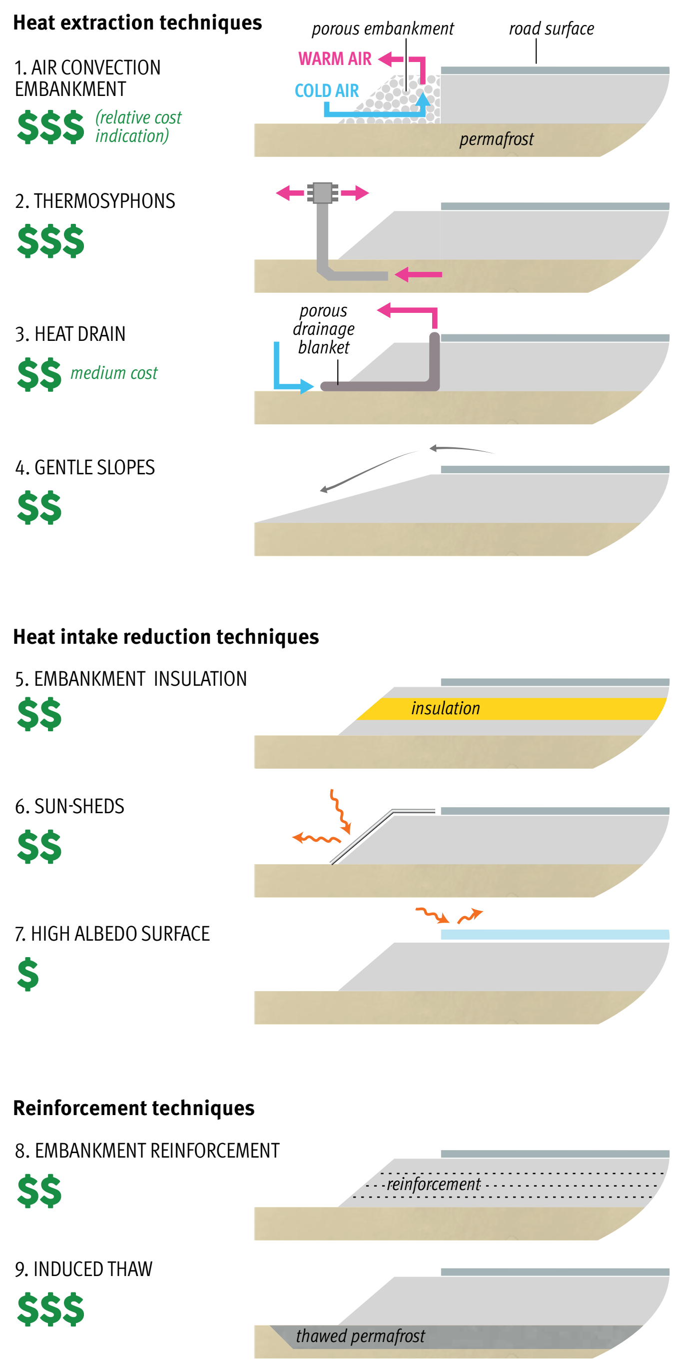
In addition to better planning, there are three broad approaches to protecting infrastructure from the impacts of thawing permafrost: heat extraction, heat intake reduction, and reinforcement. Heat extracting methods emulate winter conditions to cool embankments. The aim is to remove accumulated heat in the embankment thereby reducing the impact of infrastructure on the thermal structure of the ground. Techniques include air convection embankments that reduce summer warming and enhance winter cooling, air ducts to capitalise on local wind conditions, heat drains, thermosyphons, and sloped embankments to limit snow accumulation.

The sun is a major source of heat during the Arctic summer. Methods to reduce or prevent heat intake focus on limiting the amount of energy that gets transferred to permafrost. This may be achieved through insulation, building on piles, using materials with higher albedo (reflection), or using sun-sheds to deflect sunlight away from vulnerable infrastructure.

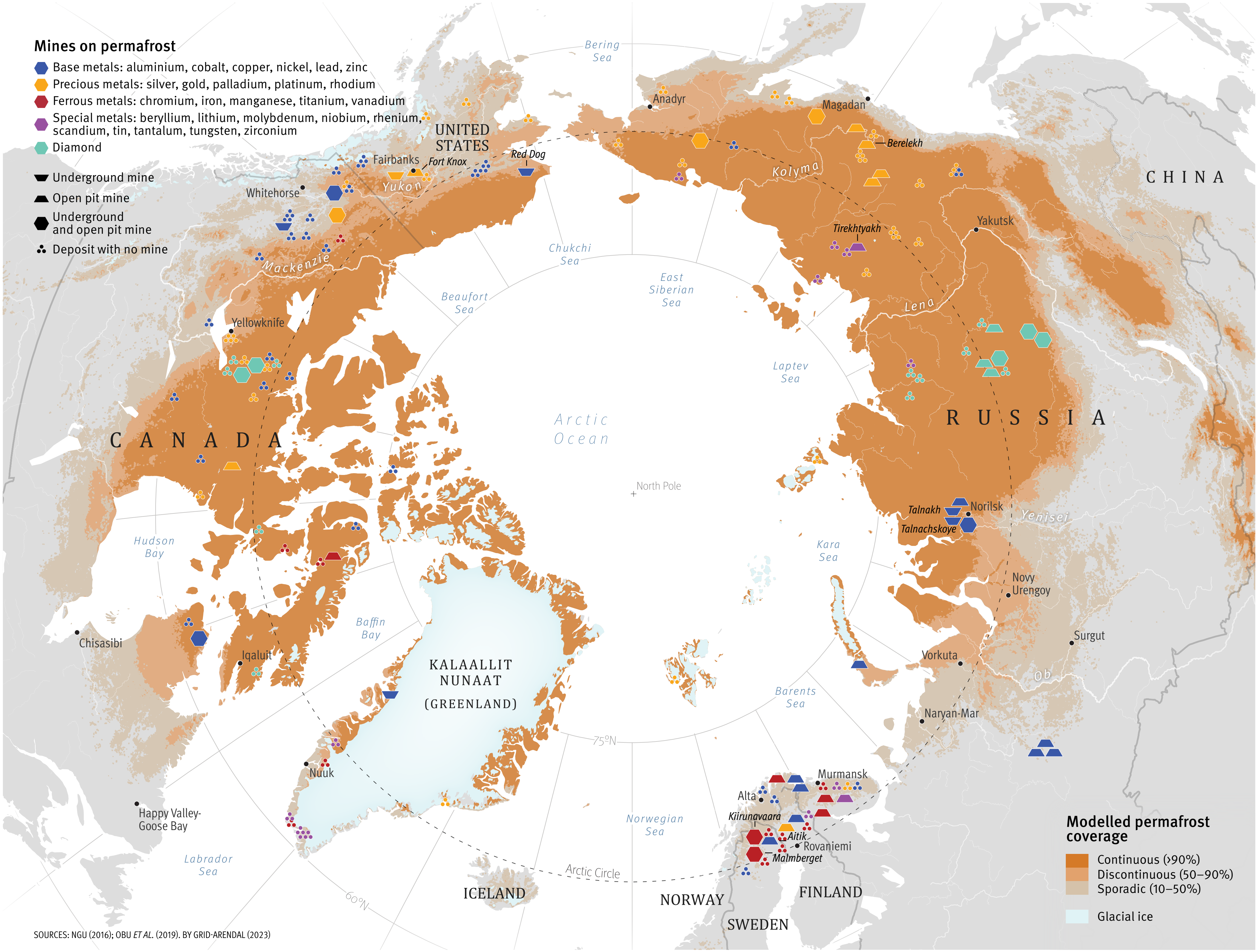
Reinforcement methods used to limit permafrost degradation around infrastructure include strengthening embankments and using controlled thawing prior to the construction of embankments. Sections of the Alaska Highway, for example, use pillow embankments while the Inuvik-Tuktoyaktuk Highway in the Northwest Territories, Canada is testing the use of woven geotextile to mitigate slope movements.



Mitigation methods for transportation infrastructure



SOURCE: HJORT *ET AL.* (2022). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



SOURCES: NGU (2016); OBU *ET AL.* (2019). BY GRID-ARENDAL (2023)

Undermined

Mining infrastructure and permafrost

While all Arctic nations have mining operations, only Canada, Kalaallit Nunaat (Greenland), Russia, and the state of Alaska have operations in permafrost landscapes. In Alaska, gold and zinc are the main minerals being extracted (except for oil and gas), and the industry is a significant contributor to the region's economy. Diamond mining also plays an important role in the economy of northern Canada, especially in the Northwest Territories. In Kalaallit Nunaat, mining only accounted for 0.4 per cent of the gross regional product (GRP) in 2018, but this sector is likely to increase in the coming decades as Kalaallit Nunaat is home to some of the largest mineral deposits in the world, including rare earth minerals. A large share of the world's mineral extraction occurs in Russia's vast territories, including iron and ferro-alloy minerals, non-ferrous minerals, precious metal ores, and industrial minerals. Combined with petroleum extraction, these sectors constitute 60 per cent of the Russian Arctic's GRP.

Many mines in the Arctic are found in areas impacted by permafrost thaw, and subsequent landscape changes are creating challenges and risks for these operations. Mining infrastructure can impact the energy exchange between the surface and the atmosphere, known as the surface energy balance, which may cause local thawing. The accelerating permafrost thaw caused by global warming, however, has the potential to change the landscape even more drastically. While permafrost thaw will not make mining in the Arctic impossible, it will have consequences in terms of safe operations, particularly when it comes to impacts on freshwater systems and the secure storage of mine tailings.

Tailings are a byproduct of mining, comprising a mixture of solids and fluids used in the extraction process. In the Arctic, permafrost has been an effective barrier in tailing deposits, preventing contaminants from seeping into the environment. However, as permafrost thaws and the ground ice within it melts, the hydraulic conductivity increases. This means that water, along with any dissolved elements, can move more easily and potentially infiltrate groundwater or local water bodies. As a result, relying on permafrost for tailings containment is no longer a viable option and other solutions are needed.

One way to ensure containment of tailings is to reinforce the physical strength of deposits through thick gravel covers or dry stacking. The latter approach aims at reducing the moisture levels in tailings to lower the risk of seepage and minimise the risk of catastrophic failure. Another option to secure tailings is using thermosyphons, a device designed to cool the ground by extracting heat from the soil to impede thawing below and around tailings dams.

Mining projects should build on collective knowledge through the sharing of experiences across the Arctic as a way of contributing to best practices for safe and sound operation in the region. For example, the International Council on Mining and Metals, a membership organisation consisting of mining companies operating across the globe, has recognised permafrost as a potential risk factor in the years to come, particularly for mines that have long life spans. The design of mines should be holistic in the sense of meeting the diverse challenges linked with Arctic mining. These challenges include remoteness, limited infrastructure, harsh weather conditions, water availability, climate change, and the long-term stability of tailings. Planning for a future where permafrost conditions are changing will be fundamental to ensuring a holistic design. Such designs should always include scenario modelling, for example, by studying how ground and hydrology will change as the ground warms.

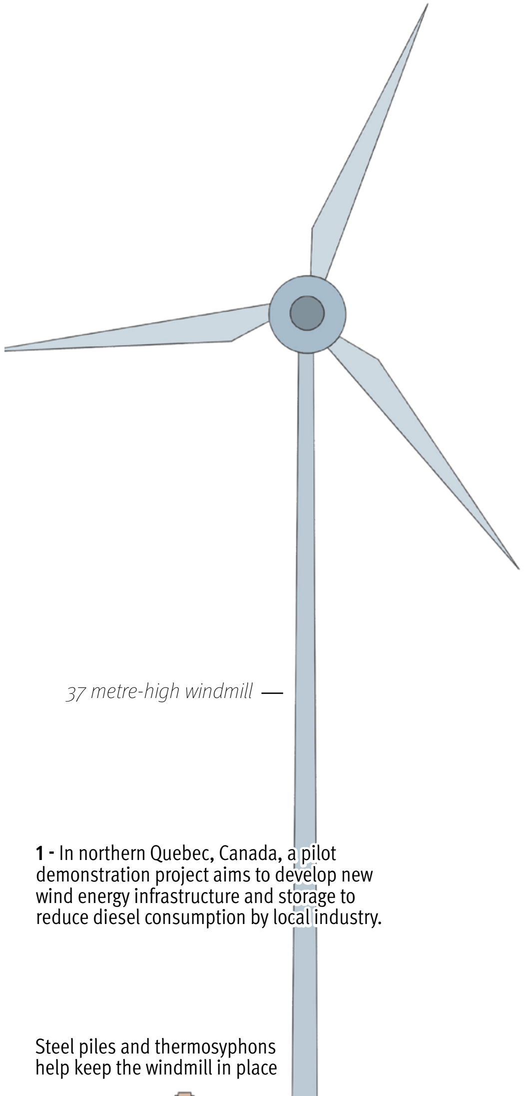
Keeping the light on

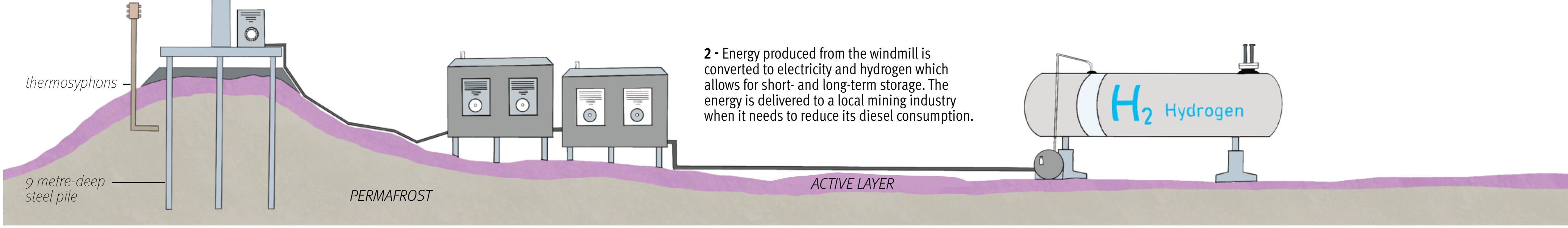
Energy infrastructure and permafrost

With great distances and long cold and dark seasons, access to energy is essential in the Arctic. These same factors, however, also put pressure on energy security. Fossil fuels remain the primary source of energy throughout the Arctic region. To cope with the increasing costs of fossil fuels and help reduce greenhouse gas emissions, some communities are considering alternative sources of energy. For example, in Kalaallit Nunaat (Greenland) 70 per cent of energy comes from renewable sources, mainly hydropower. Two major hydropower plants have been constructed in permafrost areas. The difficulty of building on permafrost, coupled with increasing permafrost thaw, pose challenges to all types of energy development.

Many communities, especially those in remote and isolated areas, rely on fossil fuels that must be transported long distances, often from outside the Arctic. As thawing permafrost impacts transportation infrastructure like roads and runways, it may also affect the energy security of many communities. In Russia, for example, changes in permafrost are one of several factors that have left the infrastructure supplying Russian Arctic communities with energy at risk. Because of unstable deliveries, fuel costs have risen. With an increase in Arctic oil production, a short-term improvement can occur. Eventually, however, the energy mix will need to be diversified and the benefits may not weigh up against potential impacts on the environment.

Together with communities, government, and private partners in Nunavut, Canada, WWF is developing small-scale energy infrastructure. The project includes constructing solar panels to provide energy for community freezers and other needs. Freezers are important for communities where hunting and fishing are widely practised, and the need for them is greatest during summer when the temperatures are high and daylight hours are long. Ice cellars in permafrost have long been used for storing food, but permafrost warming means that temperatures in the ice cellars are too high to store food safely and, in some cases, the cellars thaw out. Freezers running on energy generated from solar panels can be a potential sustainable alternative for these communities.



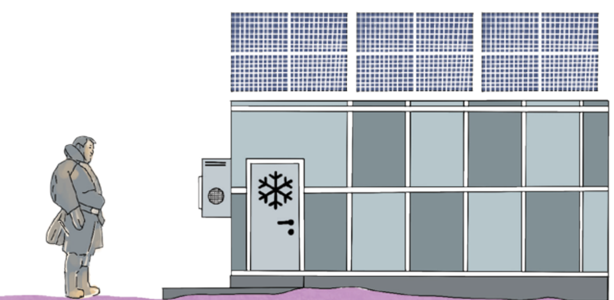


Wind farms in permafrost regions face unique challenges. Constructing wind turbines requires heavy equipment that may damage the underlying permafrost. The turbines also require strong and stable foundations to counter the stress exerted on the structure when in operation. Problems can emerge as thawing permafrost weakens the integrity of the ground.

Numerous techniques have been developed to adapt wind turbines to permafrost landscapes. In southwestern Alaska, helical piers were dug 11–12 metres below the surface to anchor the steel and concrete foundations in deeper layers of the ground. In Nunavik, Canada, a pilot windmill built in 2014 used a pile-mounted foundation that extends below the active layer in a “spider-like steel foundation”. In addition to stabilising the foundation for future permafrost thawing, the project also reported a 90 per cent reduction in concrete needed for the foundation, highlighting its benefits for remote Arctic areas. Other adaptation methods being used or tested include the use of heavier foundations to ensure stability, controllers that adapt turbine operations to changing ground conditions, and mechanisms to reduce structural vibrations.

Many permafrost landscapes are suitable for hydropower and changing climate conditions can make new areas attractive for development. Hydropower has already been extensively developed in high altitude alpine landscapes to harvest the energy of flowing water on steep gradients. Also, as precipitation is predicted to increase in the Arctic, more hydroelectric power can be harvested in the north. Planning for changing climate with altered hydrological and ground conditions and accounting for the impacts of enlarged water reservoirs on permafrost thaw should be central in the future development of hydropower in the Arctic and in high mountain regions.

When permafrost thaws, water can percolate through the previously frozen ground and enter the subsurface layers. Depending on factors such as whether the permafrost is continuous or discontinuous, this process can change the run-off and impact the water availability for hydropower plants. To plan for future changes, there is a need to use modelling of both climate and local hydrological structures. The development of such models also includes sharing and communicating results to relevant stakeholders involved in hydropower development, as well as conducting proper environmental impact assessments.



3 - In Nunavut, Canada, a village installed a solar-powered community freezer. It provides space to store harvested meat and fish, especially in the warmer and longer summer months. Reducing the reliance on diesel also provides an alternative to ice cellars.

No time to waste

Waste management and permafrost

Contrary to the image of the Arctic as a pristine landscape, the region does have waste management issues. Arctic cities, for example, produce more waste per capita, recycle less, and have lower rates of waste collection than the global average. Waste can also be an issue for many Indigenous communities whose traditional lifestyles produce little inorganic waste but who, in more recent times, have adopted a more urban lifestyle. Proper waste disposal is important not only for the storage localities themselves but also for the health of the wider environment. Thawing permafrost is affecting storage facilities in many places, making this an urgent problem in need of further research.

There are significant differences in the types of waste produced between large urban centres in the Arctic and small remote communities. A large city, such as Anchorage, with a large population and diversified economy produces a larger variety of waste, including hazardous waste, compared with a small settlement, such as Unalaska, where the king crab fishery is the biggest economic activity. A study conducted by the Arctic Council's Sustainable Development Working Group (SDWG) identified several factors that influence successful waste management. These include accessibility, population size, and access to government support and funding. Connectivity to regional waste facilities serving a larger population, for example, allows access to equipment and maintenance which are not available to smaller communities without road access. Having an engaged community with local champions is also important for developing appropriate waste management systems, as is the support of regional and national governments for local communities in this task.

Landfills on permafrost need to be treated differently than those in warmer climates. Permafrost is sensitive to disturbance, so digging holes for landfills or removing the insulating cover will affect the permafrost stability. As such, above-ground freezeback landfills are preferred in many Arctic communities as this technique does not require digging deep into the ground. In freezeback landfills, the top waste will completely or partially freeze because of the cold climate and can thus be contained. Permafrost is also used as an impermeable bottom layer, preventing leakages into the surrounding environment.

The design of freezeback landfills vary. In the Alaska Administrative Code, for example, some landfills in permafrost regions can be exempted from certain regulatory rules such as having a liner (an impermeable barrier between the landfill and surrounding areas used to avoid leakages) and monitoring of groundwater impacts. This exemption is based on the premise that a freezeback design is developed where permafrost is maintained and that the waste will remain frozen during and after the lifetime of the landfill. Some landfills, however, cannot accomplish freezeback and in such instances a frozen barrier can be developed around the landfill.

While relying on permafrost as an impermeable layer might be a functional design in today's climate, increasing temperatures will take away this option in many places across the Arctic. If the underlying permafrost layer thaws, contaminants can seep into and pollute the surrounding environment, rivers, and groundwater. In addition, the waste itself can cause local thawing in and around waste landfills. The actual amount of heating depends on the type of waste that is stored. Dumps of coal fragments, for example, can produce heat due to oxidation, while municipal solid waste sites produce heat through decomposition. When the permafrost around a landfill thaws, unfrozen areas in the permafrost known as talik zones are created under the waste, and leakages from the dumps into water and the ground can occur. If taliks are allowed to develop, the ground can eventually collapse, forming thermokarst depressions. While some adaptation options exist (e.g., strengthening landfill embankments, introducing air convection embankments, and thermosyphons), better technologies are needed in this area.

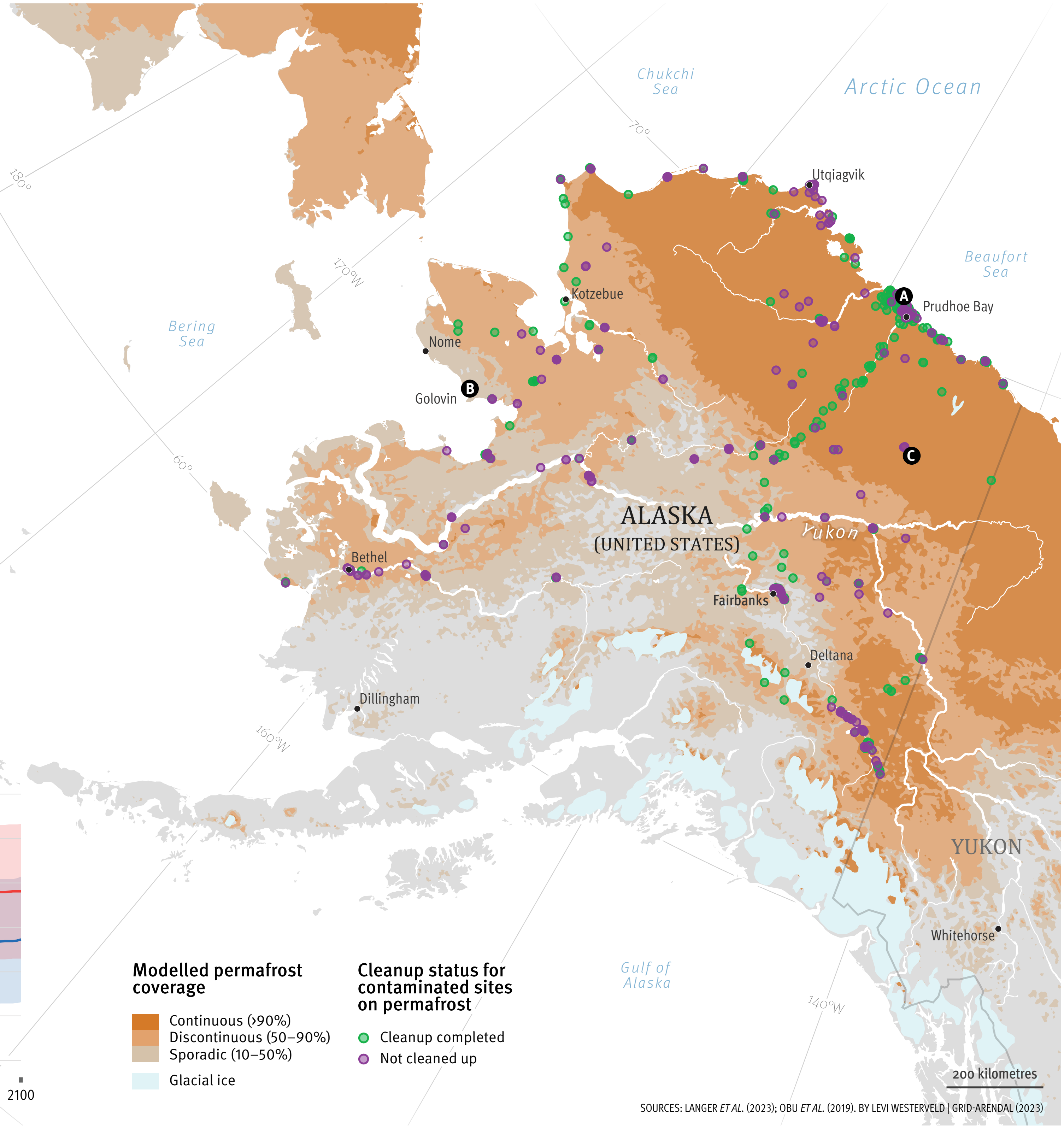
Dumps and landfills on permafrost have several potential concerns associated with them. It is therefore important to ensure that they are properly constructed and managed to both contain waste securely and prevent permafrost thaw. To be cost-effective, governments can also apply land-use planning and risk maps as practical tools to locate and target the most hazardous areas in need of new engineering solutions.

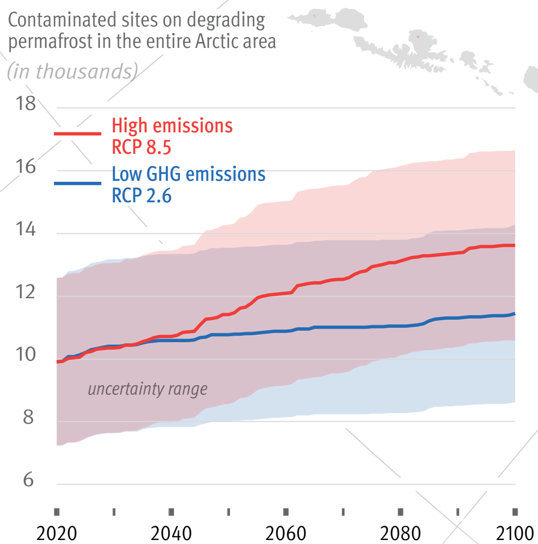
Laws and regulations play an important role in ensuring proper waste management, but not all Arctic states have paid attention to the special conditions of permafrost landscapes. For example, the Russian strategy for household waste adopted in 2013 does not specifically mention permafrost regions. Developing such strategies will be beneficial in the long-term considering the pressure on permafrost landscapes.

A **Point McIntyre** was a historic military base, whose landfill was under pressure from the eroding coastline. To prevent pollution, a process to move the landfill further inland started in 2013. A freezeback technique was applied to the landfill to ensure containment of waste.

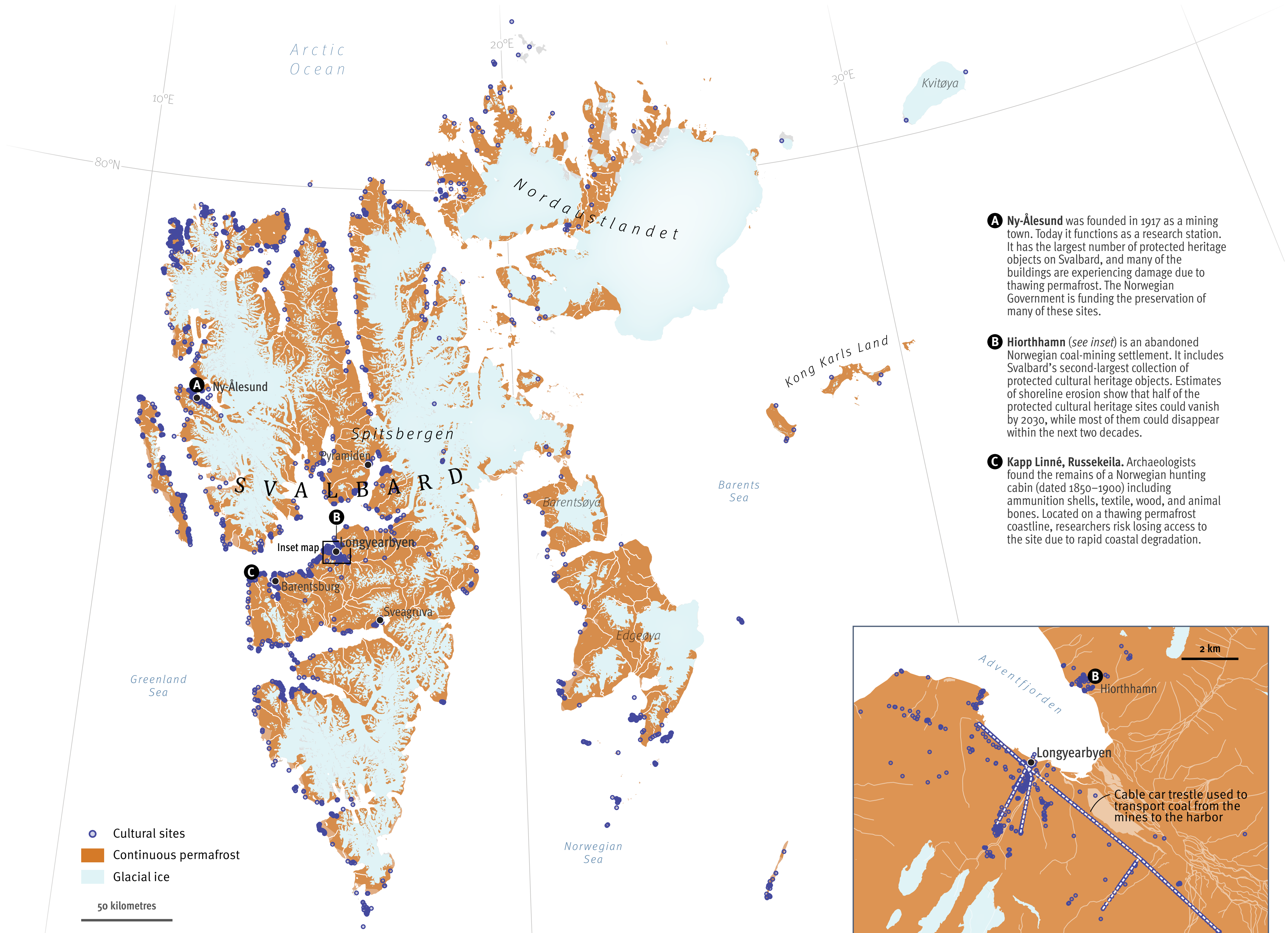
B **Golovin** is listed in the 2019 Sustainable Development Group Report (SDWG) on best waste management practices in small and remote Arctic communities. In Golovin, trench cells are dug down to permafrost, which works as an impermeable layer. The SDWG report highlights the landfill operator as a local champion, the community's work with maintaining a clean and organised landfill, as well as its good maintenance programme as areas to be inspired by.

C **Arctic Village** was one of the pilot sites for the statewide Backhaul Alaska programme. Backhauling is the process of taking waste out of a community to a location with more adequate waste systems. While expensive, this is sometimes the best solution to avoid pollution.





SOURCES: LANGER *ET AL.* (2023); OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



SOURCES: NORWEGIAN DIRECTORATE FOR CULTURAL HERITAGE (2022), OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Modern history

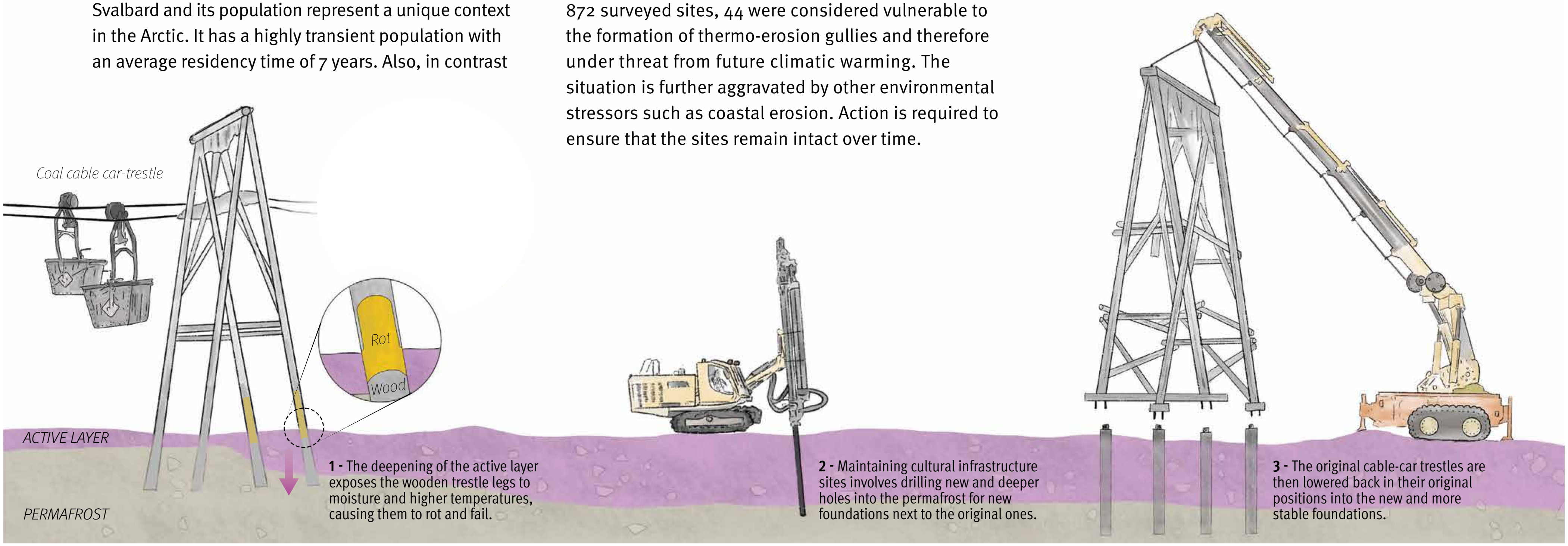
Preserving Svalbard's cultural heritage

The Arctic region has a rich and diverse cultural history which has left behind a myriad of cultural heritage sites. Arctic culture is conserved through people who continue to practice their traditional and Indigenous livelihoods. These livelihoods and cultural heritage, however, are under increasing pressure from the impacts of climate change, among other threats. The foundations of older buildings and infrastructure are of various quality, and as permafrost thaws, cultural heritage sites are at risk of damage and potential collapse. While technological solutions are available to protect cultural heritage sites (e.g., reinforcing foundations or building protective barriers), there are limitations. Chief among these is the issue of cost, a problem exacerbated in the Arctic due to the high cost of transporting tools, materials, and personnel.

Svalbard and its population represent a unique context in the Arctic. It has a highly transient population with an average residency time of 7 years. Also, in contrast to many other Arctic communities, the island was not permanently inhabited until mining operations started in the early twentieth century. This has resulted in a sense of place which is different from other parts of the Arctic where culture can be traced back through ancestral history. Cultural heritage sites, therefore, play an important role on Svalbard as the built environment helps preserve a particular historical and cultural identity. Svalbard's heritage sites hold international importance as they represent unique stories of human settlements.

The Svalbard Environmental Act states that all structures and sites dated before 1946 are automatically protected. The island has 8,300 officially registered cultural heritage sites spanning from buildings and infrastructure to graves and protected cultural environments. Researchers found that out of 872 surveyed sites, 44 were considered vulnerable to the formation of thermo-erosion gullies and therefore under threat from future climatic warming. The situation is further aggravated by other environmental stressors such as coastal erosion. Action is required to ensure that the sites remain intact over time.

The Polar Climate and Cultural Heritage project highlights three values that compete in the current cultural heritage system on Svalbard. The antiquarian value is related to a conservationist attitude where authenticity and research interests are most important. A more pragmatic user value argues for an emphasis on the practical value of buildings and property. Finally, the experiential value addresses the holistic experience that both visitors and residents have when interacting with cultural heritage sites. These value systems can be complementary, although controversies sometimes arise. For example, while the actors with a user value may be interested in applying modern and efficient building techniques to protect and restore heritage sites, doing so could decrease their antiquarian value.



1 - The deepening of the active layer exposes the wooden trestle legs to moisture and higher temperatures, causing them to rot and fail.

2 - Maintaining cultural infrastructure sites involves drilling new and deeper holes into the permafrost for new foundations next to the original ones.

3 - The original cable-car trestles are then lowered back in their original positions into the new and more stable foundations.

PORTRAIT ADVISOR AT KINGS BAY AS, NY-ÅLESUND, NORWAY

Ingrid Rekkavik

Part of why I ended up in Ny-Ålesund was that I've always been a bit restless. I became interested in cultural monuments and what you can learn from them and decided to become an archaeologist. Cultural heritage is exciting because people are exciting. Cultural monuments can tell us how humans at different times and in different locations have used their intelligence, skills, and creativity to survive and give life meaning.

At 79 degrees north, Ny-Ålesund is the northernmost community in the world, and the last company town in Norway, run by Kings Bay AS. Today we run a research station, and in summer up to 150 people live there. But in the winter, we are only around 35 permanently employed people here. Ny-Ålesund was originally a mining community, founded in 1916, but coal production ended in the 1960s. The buildings here give us a window into the past and can tell us a lot about the hopes, creativity, and perseverance of the people who lived here before us. Miners came here in the fall, knowing they would be stuck in total darkness and isolation for 6 months. Witnessing how they were able to live in rather pitiful conditions, compared with the standards we have today, is inspirational.

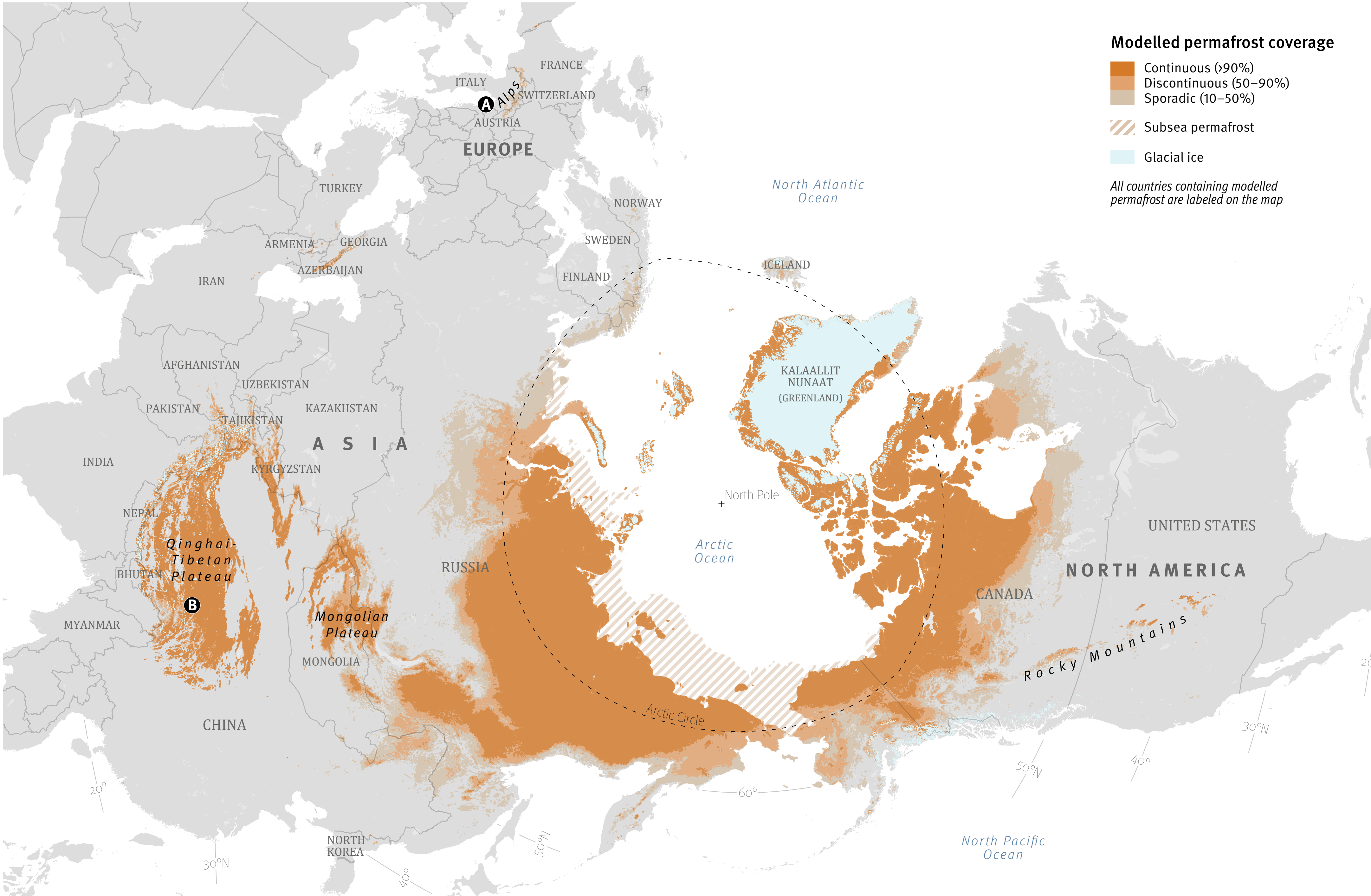
I first encountered permafrost when I started working in Svea, another old coal mine in Svalbard. I quickly learned that it's not easy to dig in the ground. We had to wait until it was the right season or wait for weeks until the sun heated up the ground sufficiently before we could start digging decimetre by decimetre. Even large 30-ton excavators could not get through. During that time, I gained a practical understanding of concepts like the active layer. I was familiar with frozen ground from archaeology on the Norwegian mainland, but the frost here does not come from cold air above ground, but rather from below.

In my earlier work in Svea, I also learned a lot from more experienced colleagues, miners, and people that have lived on Svalbard for a long time. They told me how things were changing, and how the permafrost was more stable and reliable. All the buildings in Ny-Ålesund are built on permafrost, so we are dependent on it. When the permafrost thaws deeper and deeper every year, it impacts the buildings. The posts that the buildings are standing on are frostjacked, but often unevenly which further affects the stability of buildings. It can create a lot of issues, and changes have accelerated. And it's not only the houses. Suddenly a stretch of road disappears. Everything is suddenly a bit less stable. When you live 1,000 kilometres away from the nearest major settlement, you have to think about what that means for community safety and emergency preparedness.

In Ny-Ålesund, we have Svalbard's largest collection of protected buildings. We have 29 buildings under the strictest form of preservation built in 1909–1945, but a total of 40 buildings are considered to have cultural value. It's a lot of responsibility, because this is a cultural heritage on a national level from the mining period. When it comes to fixing the foundation of old buildings, we have to consider how big the historical value is when measured against the usefulness and economic cost of maintaining a building. We have to weigh advantages and disadvantages. Gradually, it's getting more and more expensive to deal with the impact of climate change. So how much time, money, and material should we use to save historical monuments? At some point we have to prioritise more.

Going South

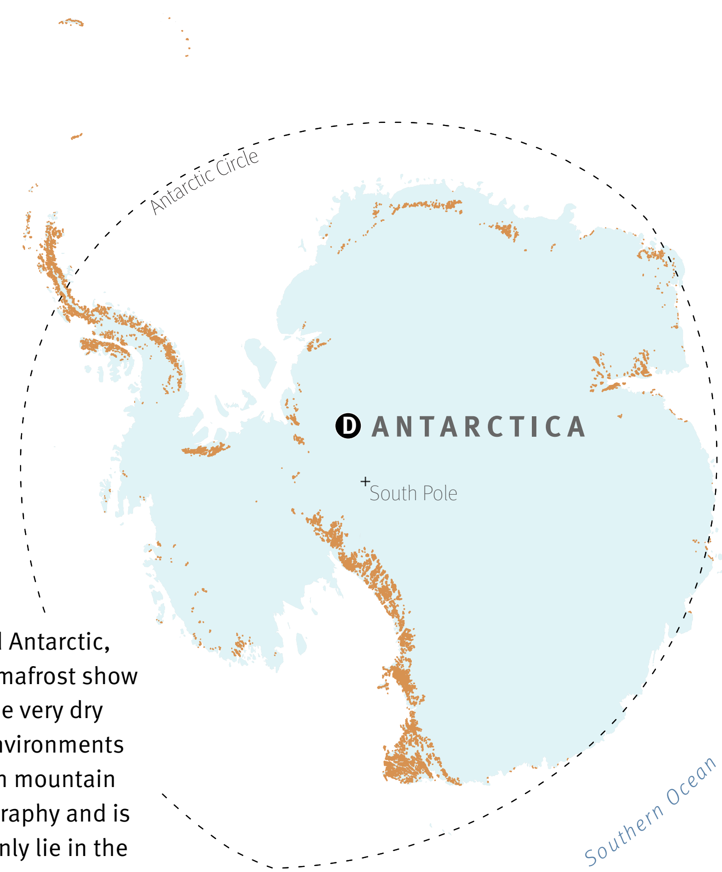
Permafrost in Other Areas



A **In the Alps,** permafrost thaw is leading to more rockfalls, affecting mountaineering and mountain tourism, making many popular climbing routes more dangerous.

B **The Qinghai-Tibetan plateau** has the largest store of alpine permafrost on Earth. Warming temperature may cause as much as 70 per cent of it to disappear by 2100.

SOURCES: OBU *ET AL.* (2019a), (2019b), (2020); OVERDUIN *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)



C Rock glaciers in **the Andes** are underlain by an ice-rich permafrost layer and are thought to be important seasonal contributors to stream flow and thus, water security.

D Permafrost occurs within most of the ice-free areas of **the Antarctic**, less than 0.2 per cent of the continent. It might exist under the massive Antarctic ice sheet but there is no direct evidence of it.

A planetary perspective

Permafrost outside the Arctic

Permafrost also occurs outside of the Arctic, in the ice-free areas of the Antarctic, and at high elevations around the globe where the temperature remains below 0 °C for much of the year. Permafrost occurs extensively in mountainous areas across the Qinghai-Tibetan Plateau, in the Hindu Kush Himalayan region, Central Asia, and Mongolia, as well as throughout the South American Andes, the European Alps, the Rocky Mountains of North America, and even on Hawai'i (not shown on map).

While there are some similarities between polar and mountain permafrost, there are also significant differences. Compared with the Arctic and Antarctic, for example, mountainous areas with permafrost show an extreme range in precipitation, from the very dry conditions of the Andes to the very wet environments found in Norway. Permafrost occurrence in mountain areas is strongly controlled by local topography and is most likely to occur in places that commonly lie in the shade, as well as in valleys with steep sides located at higher latitudes. These factors lead to a much higher degree of spatial heterogeneity (patchiness) in mountain areas with permafrost than in polar environments where permafrost is more often spatially continuous across vast areas.

Frozen giants
Permafrost in the mountains

Outside of the Arctic, permafrost most commonly occurs in high mountaintops. It is most pronounced on the north-facing slopes in the northern hemisphere and south-facing slopes in the southern hemisphere. With decreasing elevation, permafrost becomes less extensive and more discontinuous, isolated, or sporadic until it disappears all together. In addition to latitude and altitude, the presence of permafrost is also determined by precipitation, seasonal and daily temperature extremes, air humidity, soil moisture, and geology.

Direct observations of permafrost cannot be made using remote sensing technology, and so permafrost mapping depends on sparse ground temperature measurements that are augmented by extrapolation and interpretation. Observational data, in turn, are unevenly distributed among and within different regions, and sampling strategies vary locally. For example, in the European Alps, permafrost is often observed at high elevations or on the summits of mountains, whereas on the Tibetan plateau sampling is mainly done for practical applications, such as along roadsides to monitor thawing.

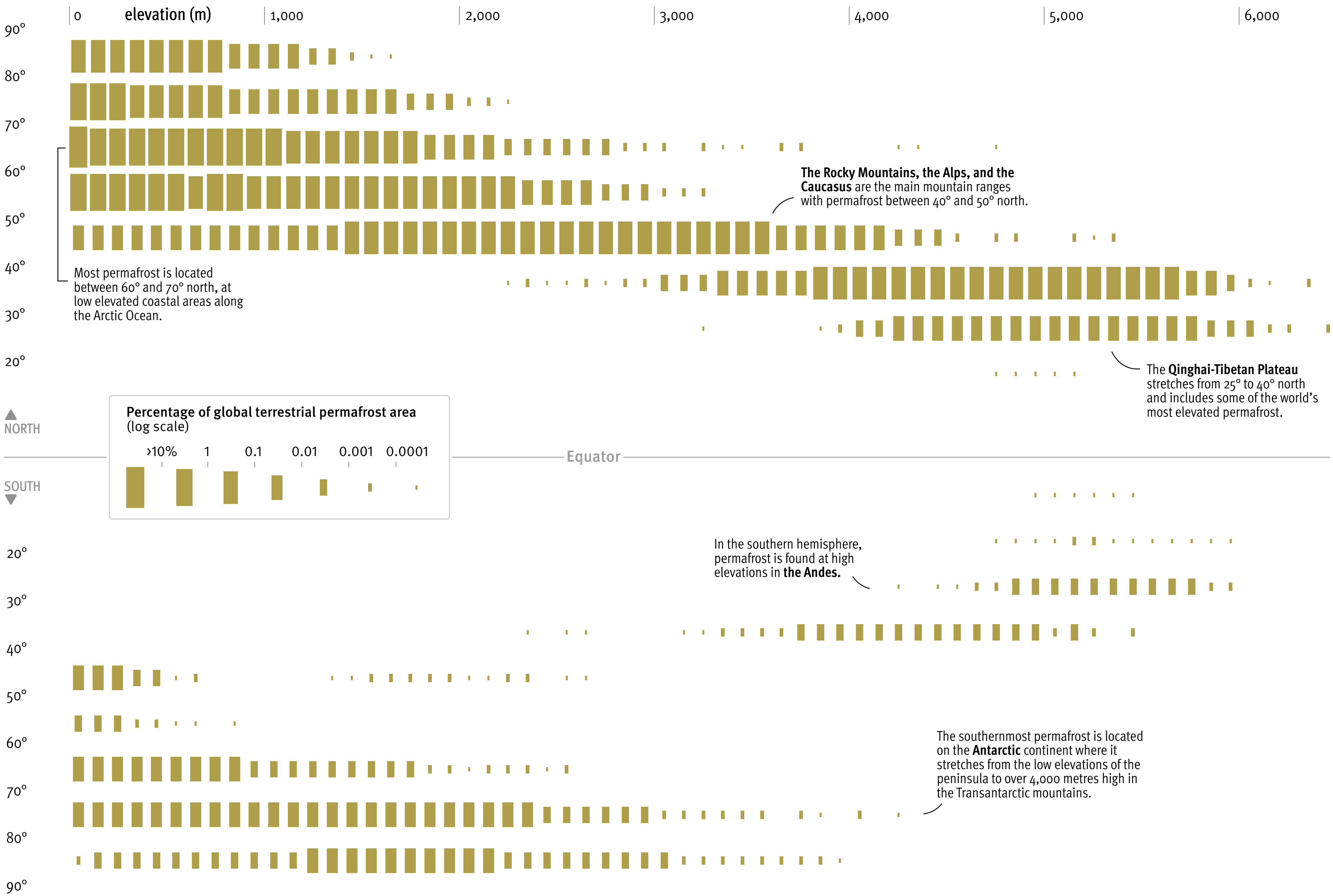
These different observational techniques can bias analyses of permafrost occurrence. When combined with the environmental factors mentioned above, this leads to a high degree of uncertainty in models of permafrost occurrence in mountains, as well as in its response to global climate change. Regardless, evidence shows that higher temperatures resulting from anthropogenic global climate change are causing permafrost to thaw. Although measurements are sparse and unevenly distributed among mountain regions, existing data indicate warming has occurred by 0.14–0.24 °C per decade on average for 28 mountain sites in Asia, Canada, the European Alps, and Scandinavia.

As in the Arctic, the impacts of thawing mountain permafrost can be quite devastating. This thawing affects water quality, increases the risk of landslides, and causes damage to infrastructure. Permafrost acts as a barrier for water so that both rain and meltwater flow over the permafrost on the land surface, feeding streams and rivers. Permafrost thaw may affect the surface and subsurface water flow when the soil permeability increases and the active layer deepens. The changes in hydrological pathways can disrupt local agriculture and drinking water supplies. Water quality is also affected by changing stream flow rates and by the release of heavy metals, sediment, and contaminants from the thawing permafrost.

The thinning and thawing of permafrost make mountain slopes unstable, which in turn increases the risk of landslides as well as rock avalanches. Both landslides and rock avalanches can lead to damaged infrastructure and loss of life, especially in densely populated areas or areas with high tourist activity. Outburst floods and catastrophic floods resulting from the sudden release of a large volume of water can be triggered by permafrost thaw in mountain lake dams. Roads, railways, and buildings that stand on permafrost are also at risk as the ground becomes less stable with permafrost thaw. In fact, the very presence of roads and buildings can cause permafrost to thaw faster through disturbance of the soil and localised heating of the ground.

There are major gaps in our understanding of the occurrence of permafrost in mountain areas and of the impacts that anthropogenic global climate change will have upon communities located in mountain permafrost regions. Thawing permafrost is impacting mountain communities. These impacts are expected to become more pronounced and more frequent with the anticipated increase in global warming.

Permafrost distribution by elevation and latitude



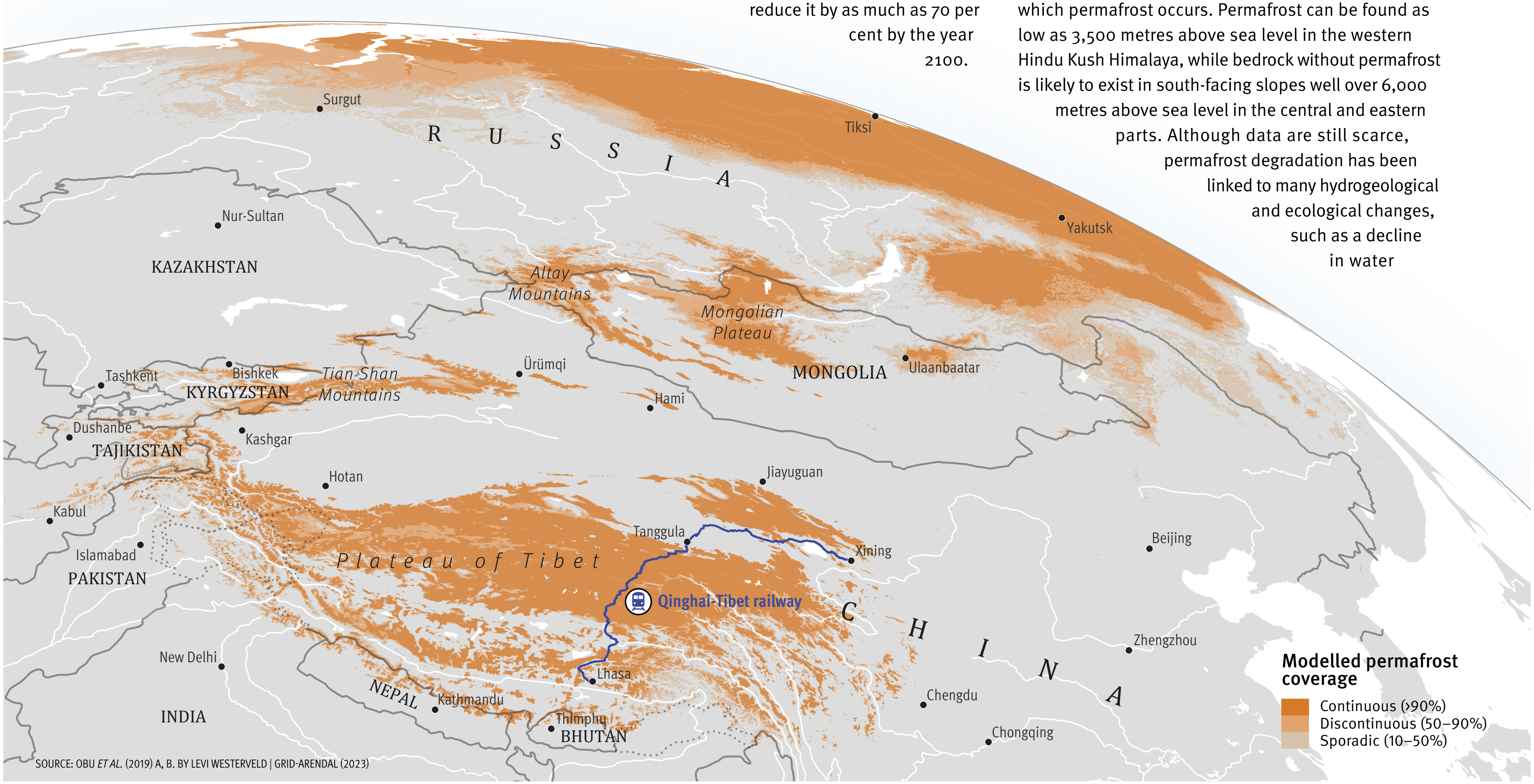
NOTE: the graphic includes all modelled sporadic, discontinuous, and continuous permafrost data from Obu *et al.* (2019).
SOURCES: OBU *ET AL.* (2019a), (2019b), (2020); SRTM (2015). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

The view from the top

The Qinghai-Tibetan Plateau, Hindu Kush Himalaya, and Andes

The largest permafrost area outside of the Arctic is found in the Qinghai-Tibetan Plateau extending to the slopes of the Hindu Kush Himalaya to the south. About 40 per cent of the plateau is characterised by the presence of permafrost, making it the largest store of mountain or high-elevation permafrost carbon on Earth. Atmospheric warming is already affecting the permafrost of the Qinghai-Tibetan Plateau, with recent computer models predicting that climate change may reduce it by as much as 70 per cent by the year 2100.

The Hindu Kush range is home to the world's highest mountains, including Mount Everest which reaches 8,849 metres above sea level. Large variations in topography combined with regional variations in air temperature lead to a large range in the elevation at which permafrost occurs. Permafrost can be found as low as 3,500 metres above sea level in the western Hindu Kush Himalaya, while bedrock without permafrost is likely to exist in south-facing slopes well over 6,000 metres above sea level in the central and eastern parts. Although data are still scarce, permafrost degradation has been linked to many hydrogeological and ecological changes, such as a decline in water



SOURCE: OBU *ET AL.* (2019) A, B. BY LEVI WESTERVELD | GRID-ARENDAL (2023) conservation capacity, the shrinking of wetlands and meadows, and reduced grassland productivity, diversity, and vegetation coverage.

Across the region, thousands of kilometres of roads and railways have been built in permafrost areas and are now exposed to potential damage from permafrost thaw. In addition to climate warming, the engineering activities themselves can create thermal changes that lead to permafrost degradation and result in very high infrastructure maintenance and repair costs. About 550 kilometres of the 2,000-kilometre-long Qinghai-Tibet railway from Lhasa to Xining is built on permafrost, reaching over 5,000 metres above sea level in places. To increase railbed stability, embankments of loosely piled rocks have been built to allow air to circulate freely. In some stretches, ventilation pipes buried into the ground allow the cold air to circulate underneath the railbed. The cost of maintenance and repairs is expected to increase as projected climate warming deepens the active layer above permafrost on the plateau.

The Andes are the longest mountain range in the world, extending from tropical Venezuela to the southern tip of Argentina. Conditions favourable to the formation of mountain permafrost can be found across the high-altitude areas. It is challenging to predict where this permafrost might occur, as the complex mountain topography results in extremely variable patterns of permafrost formation. Field surveys that confirm the presence of permafrost are expensive and logistically difficult. More commonly, permafrost distribution is estimated using probability models based on environmental variables, including mean annual air temperature, incoming solar radiation, topography, and elevation.

Active rock glaciers are also frequently used as indicators of permafrost presence. These distinct landforms occur because of the downslope movement, or creeping, of frozen ground and can be identified from aerial photographs and satellite imagery. Rock glaciers consist of a surface layer (the active layer) underlain by an ice-rich permafrost layer. The amount of ice in the permafrost layer is variable (10–45 per cent). The surface layer of ice, rock, and soil insulates the underlying frozen ground, making rock glaciers more resistant than ice glaciers to the impact of climate warming. The seasonal contribution of rock glaciers to stream flow, and thus water security, is thought to be important but is not well understood.

While rock glaciers and other permafrost features are less obviously affected by atmospheric warming than ice glaciers, there are signs that they too are degrading. In the Bolivian Andes, projected warming could result in the loss of 95 per cent of current permafrost (including almost all rock glaciers) by 2050, and up to 99 per cent by 2099. Climate warming can increase the thickness of the active layer, releasing water frozen in the upper permafrost. However, this is a slow process and does not result in a significant increase in seasonal flow from the active layer. Climate-induced permafrost degradation is also implicated in the downslope acceleration of some rock glaciers and an increase in rockslides and rock avalanches.

Permafrost in the Andes is also affected by mining and other forms of development that can increase the ground temperature, leading to subsidence and the formation of thermokarst. This is of serious concern because mining in the Andes is increasing, causing major changes in the landscape including the disposal of mine tailings and waste rock onto the surface of rock glaciers.

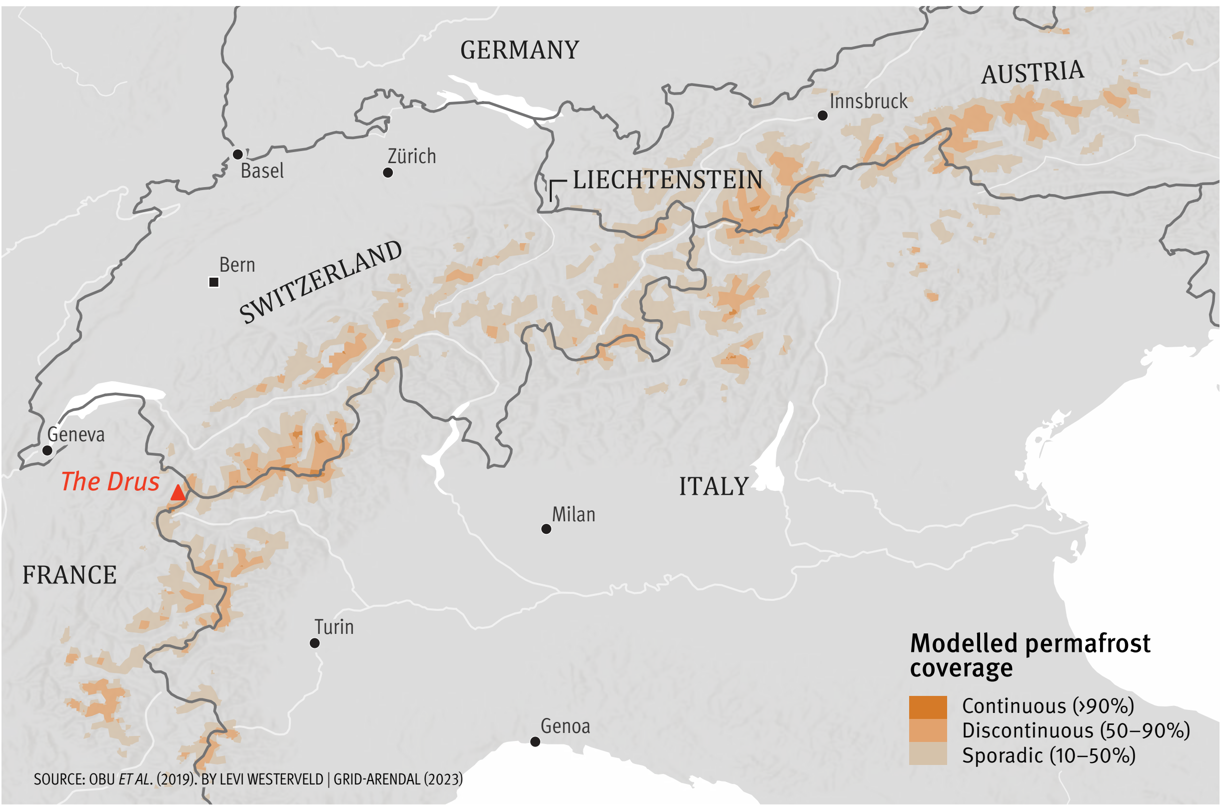
SOURCE: OBU *ET AL.* (2019). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

Europe's frozen heart

Permafrost in the Alps

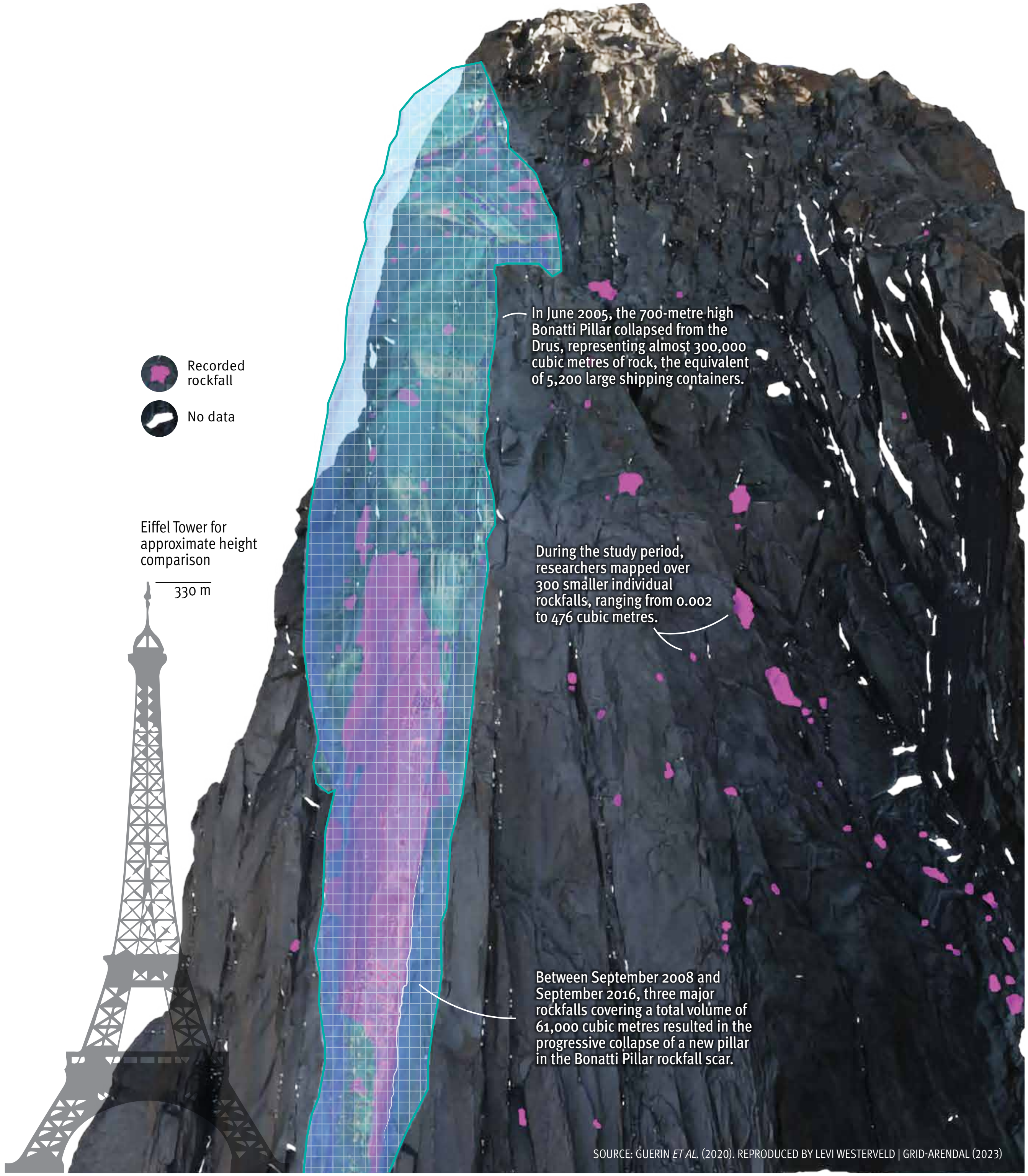
The European Alps are a densely populated and relatively accessible region in comparison to the other mountain regions of the world, making it a very popular destination for mountain tourism. Permafrost is a prominent feature in the Alps where it occurs above 2500-3000 metres elevation above sea level and underlies about 3 per cent of the surface area, with the largest portion in Switzerland, followed by Italy, Austria, and France.

Mountain permafrost is degrading due to climate warming, destabilising rock walls on the mountain slopes. In recent years, summer heat waves have triggered rockfalls in the Alps. Permafrost degradation has an increasing impact on mountaineering practices and mountain tourism in general as climbing seasons have shifted and many popular mountaineering and climbing routes have become more dangerous.



In contrast to the Andes or the Hindu Kush Himalaya, rockfalls in the Alps are small but frequent during summer. Although relatively rare, major rock avalanches also occur. The Drus (3,754 metres) mountain in the Mont Blanc massif of the French Alps has been the site of major rockfall events, which scientists attribute to a warming climate and permafrost degradation. In June 2005, the 700-metre-high Bonatti Pillar collapsed from the Drus, bringing down almost 300,000 cubic metres of rock, the equivalent to 5,200 large shipping containers. Between October 2005 and September 2016, scientists used laser technology to scan the granitic rock face. During the study period, researchers mapped over 300 smaller individual rockfalls, ranging from 0.002 to 476 cubic metres. The detailed records of rockfall frequency and volume allow researchers to better understand the role of permafrost thaw on rockfall in mountainous areas.

The European Alps are home to much permafrost research that has produced many unique permafrost data sets. These include: the longest time series of borehole temperatures in Europe from the Murtèl-Corvatsch rock glacier in the Swiss Alps, which started in 1987; annual terrestrial laser scans showing in detail how a mountain wall in Mont Blanc massif has changed over 10 years; and a long-term, large permafrost data series from the Matterhorn, one of the highest peaks in Europe. Adaptation strategies for mountain guides have also been developed in response to the changing mountain environment. These kinds of diverse data are invaluable for understanding mountain permafrost degradation and its diverse impacts on the environment and mountain tourism.



The ends of the Earth I

Permafrost in Antarctica

Covered by the largest ice mass on the planet, Antarctica is the coldest continent. The continental ice sheet, which on average is more than 2 kilometres thick, insulates the ground surface from low air temperatures and leaves less than 0.2 per cent of the surface area ice free, mostly in the coastal areas at the edges of the ice sheet and where mountains protrude above the ice.

There are fewer permafrost monitoring boreholes in Antarctica than in the Arctic, but field observations and computer modelling show that permafrost is present under almost all the ice-free areas. Permafrost might exist under the Antarctic ice sheet, especially in areas where the ice cover is thin, but as there is no direct evidence of it, very little is known about the subglacial permafrost.

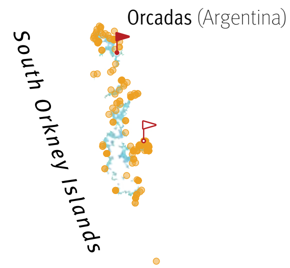
Climate and surface topography vary greatly from place to place in Antarctic permafrost areas. There is a huge latitude difference, as well as elevation range in the areas with permafrost. Ice-free areas range from the sea level to the top of the highest mountain, Mount Vinson in West Antarctica at 4,892 metres above sea level. Air temperature and the distribution of snow on the ground, the two factors affecting Antarctic permafrost temperatures most strongly, vary greatly across the continent. Antarctica is not only the coldest but also the driest continent in the world, despite many areas experiencing increased precipitation under climate change. Even if mean annual temperatures remain well below 0 °C across Antarctica, some coastal areas, especially on the Antarctic Peninsula, are warming rapidly with a tendency to above freezing temperatures.

Ground temperature as an indicator of permafrost existence has only been systematically monitored for the last two decades in Antarctica, and direct permafrost data for the continent are scarce. Sparse measurements give little information about spatial variability, and one must rely on computer models to better understand the ground temperature variability at the regional and continental scales. Modelling indicates that the coldest near surface permafrost in the world can be found at Mount Markham in the Transantarctic Mountains where the lowest ground temperature is estimated to be –36 °C.

There is no permanent human population in Antarctica. However, there are more than 80 research bases there. The number of people living and working on the continent increases to about 5,000 in the austral summer (December–February), while about 1,000 people stay over during the dark and cold winters. Many of the research stations are built in coastal areas on permafrost, where its thaw can create a potential risk for the infrastructure. Because annual mean ground temperatures are still very low, most buildings and other infrastructures are safer from the impacts of thawing permafrost than those in the Arctic. However, in some locations on the Antarctic Peninsula, permafrost thaw is having an impact on infrastructure, a problem that may become much more common under a warmer climate.

Permafrost thaw has local impacts, not only on research infrastructure but also on local hydrology. As the ground thaws, meltwater or rain will partially infiltrate the ground rather than flowing across its surface. As water is the most important physical driver of Antarctic terrestrial communities, this bears consequences for the movement of nutrients in the environment and the potential impacts on ecosystems and biodiversity. Pollutants accumulated in the permafrost may also be remobilised into the environment as a result of permafrost thaw, although more research is needed to understand their movement and environmental impacts. Unlike the Arctic, there will be lower greenhouse gas emissions from Antarctic permafrost because it contains very little organic matter. The terrestrial Antarctic could even become a short term carbon sink in the future, should vegetation expand with increasing temperatures.

SOURCES: MATSUOKA *ET AL.* (2021); OBU *ET AL.* (2020). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

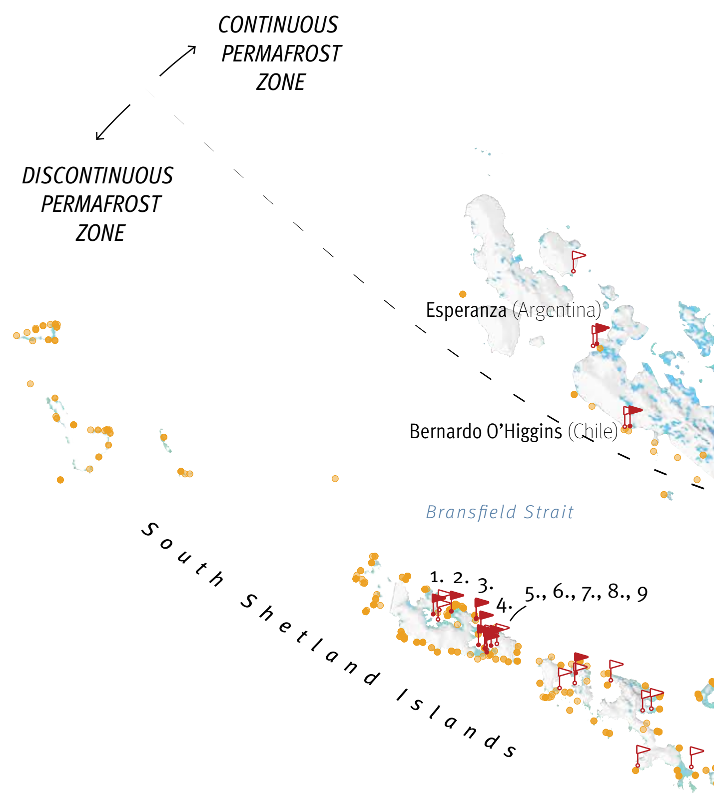


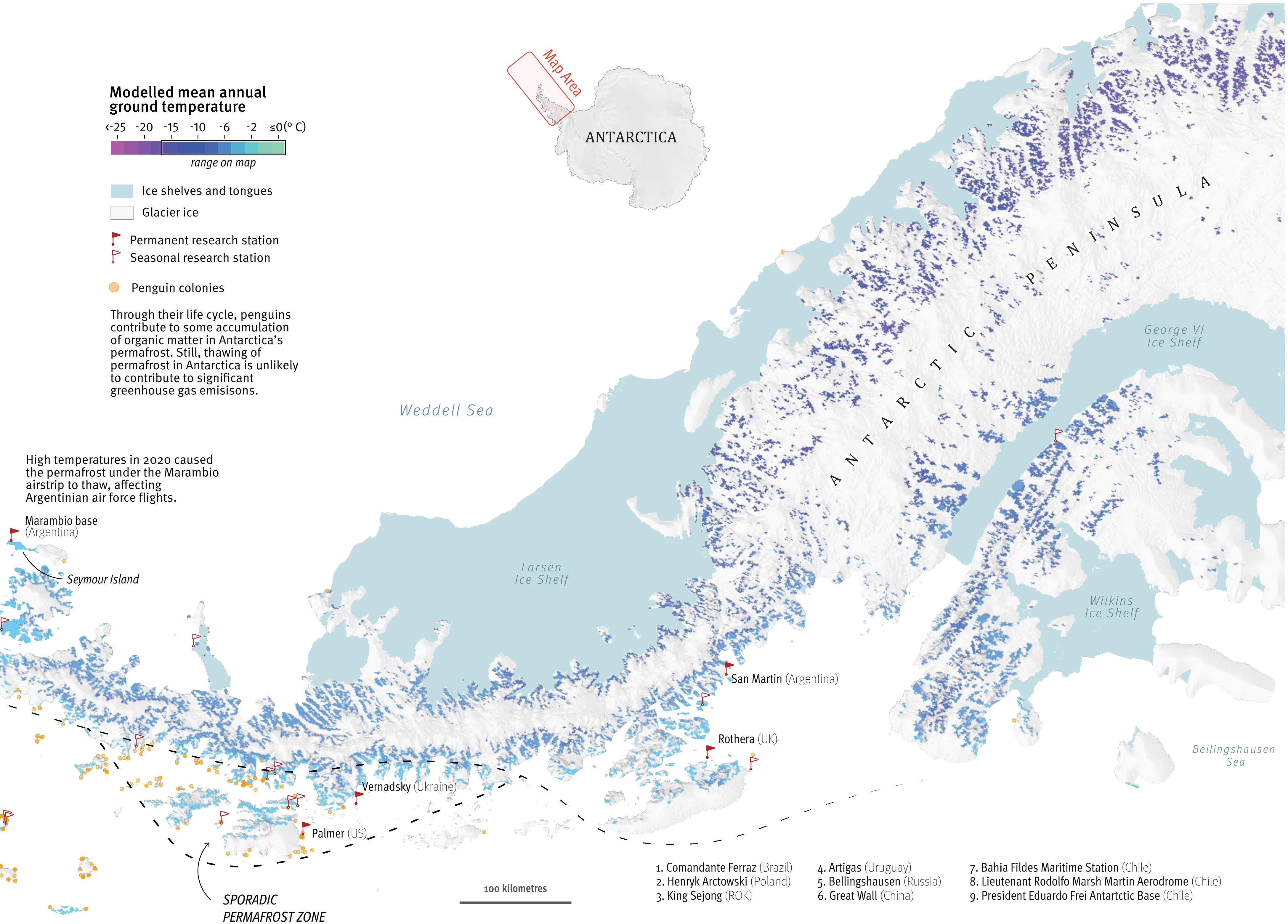
The ends of the Earth II

Antarctic Peninsula

The highest modelled near-ground surface temperatures in Antarctica are found on the Antarctic Peninsula, the northernmost part of the continent. The climatic conditions vary strongly across the peninsula, where the east coast is influenced by a continental climate, while the central and western parts experience maritime conditions. Very narrow coastal areas on the Antarctic Peninsula have sporadic or discontinuous permafrost, and the highest ground surface temperatures are found on the north-western areas of the peninsula. As elsewhere, air temperature and thickness of the snow cover play an important role for the existence of permafrost in the ice free areas.

As in other locations, thawing permafrost in the Antarctic poses a threat to infrastructure. The Marambio airstrip, which serves an Argentinian research station on Seymour Island in the Antarctic Peninsula, is built on permafrost. In 2020, the air temperature at the Argentine research base Esperanza, not far from Seymour Island, reached 18.4 °C, the highest temperature ever recorded in Antarctica, confirmed by the World Meteorological Organization. During this exceptional heat wave, flights to Marambio were impacted because the permafrost had started to thaw, transforming the surface of the airstrip to a deep watery mud which was not safe to land on. Meteorological observations on the peninsula over recent decades show an overall increasing trend in the number of such extreme warm days. Knowledge and understanding of these kinds of extreme events is important for the maintenance and safety of infrastructure such as airstrips and research stations on the continent.





SOURCES: MAPPPD (2021); MATSUOKA *ET AL.* (2021); OBU *ET AL.* (2020). BY LEVI WESTERVELD | GRID-ARENDAL (2023)

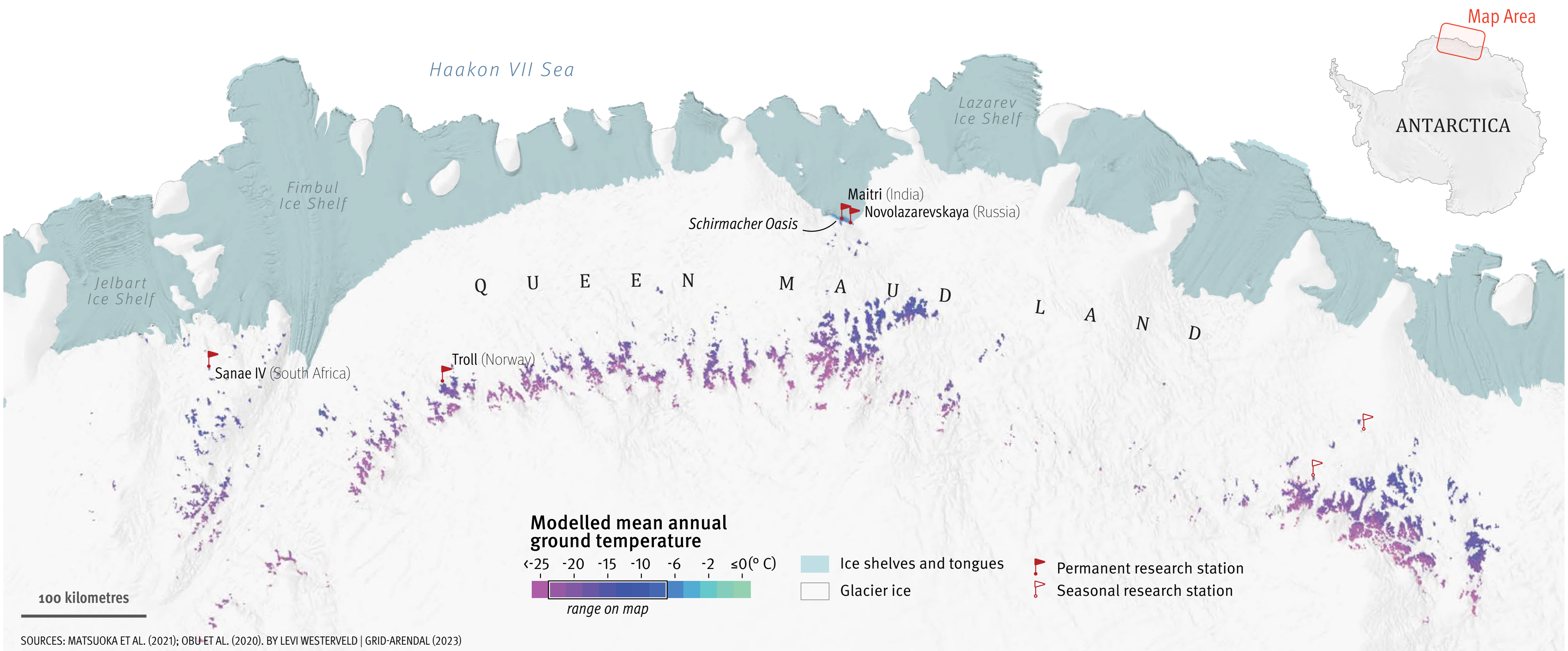
The ends of the Earth III

Queen Maud Land, Victoria Land, and the McMurdo Dry Valleys

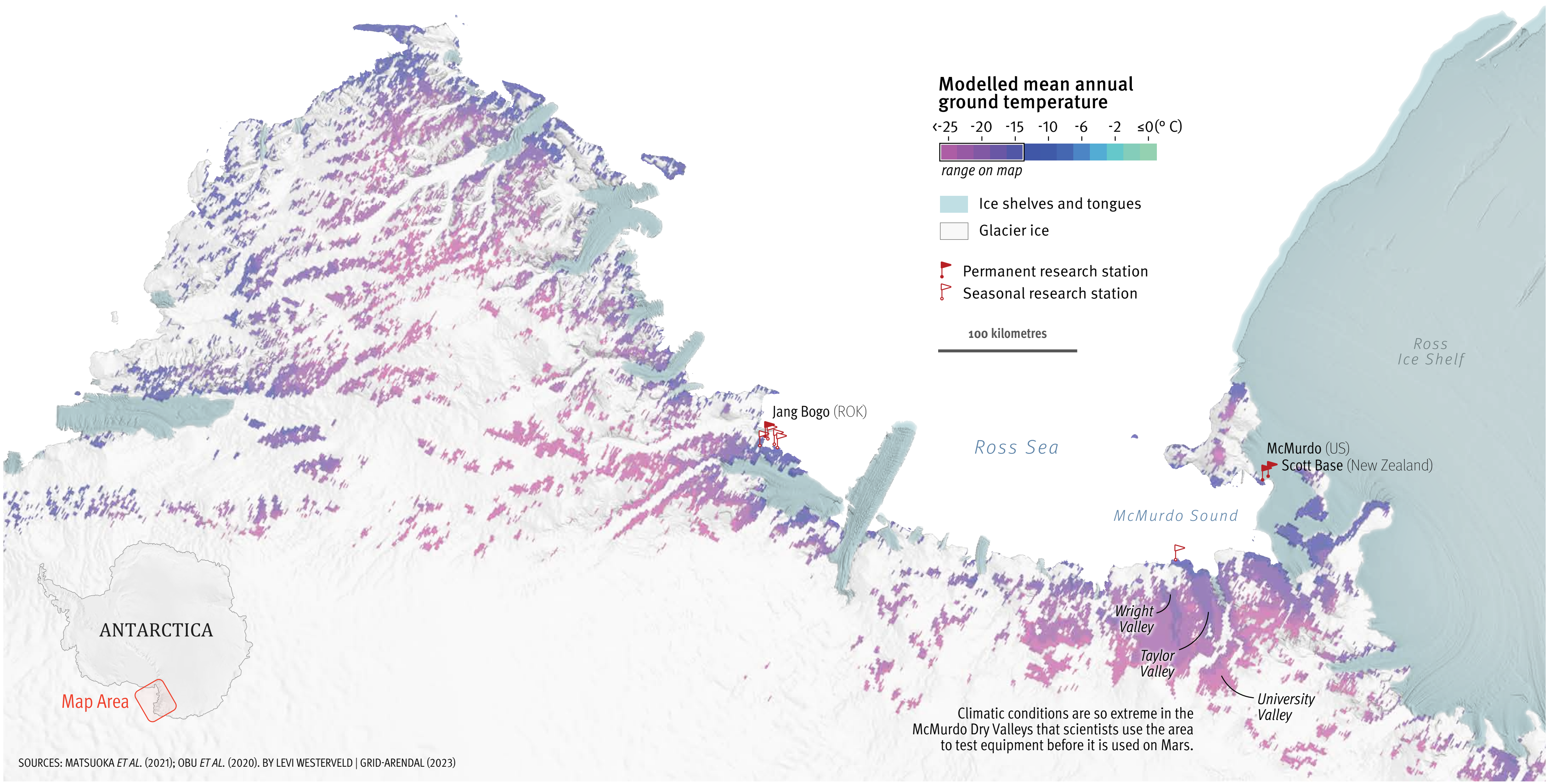
In Antarctica, cold and very dense air blows from the higher interior plateau down the steep slopes along the coast due to gravity. This process generates katabatic winds, which can be very strong at times. These winds blow down from the East Antarctic Plateau and keep large parts of the mountain ranges dry and free of snow in Queen Maud Land. The ice-free and snow-free areas of Antarctica are often referred to as oases. One of these, the Schirmacher Oasis, is an ice-free area that is 25 kilometres long and up to 3 kilometres wide, encompassing more than 100 freshwater lakes. In addition to the Indian research station Maitri located in the Schirmacher Oasis, there are 11 other research stations in Queen Maud Land, most of them built on rocky outcrops of the mountain chain where high winds keep the ground snow free.

Queen Maud Land is one region of Antarctica where an increasing trend of snow accumulation has been observed, along with rising temperatures. On the opposite side of the continent, the McMurdo Dry Valleys are among the driest areas in the world, generally classified as hyper-arid polar deserts. It is the only location on Earth known to contain dry permafrost consisting of loose soil, because its water content is very low and insufficient to cement the soil particles together. This is also the location where the oldest permafrost on Earth has been found.

The most extreme climatic conditions prevail inland at higher elevations, such as the University Valley. The



SOURCES: MATSUOKA ET AL. (2021); OBU ET AL. (2020). BY LEVI WESTERVELD | GRID-ARENDAL (2023) conditions resemble those on Mars, making the Dry Valleys a Mars analogue where scientists can study periglacial processes and geomorphic features and their use as a diagnostic for subsurface ice on Mars. In contrast to the Arctic, where active microbial populations can be found in permafrost soils, microbial activity is undetectable at the high elevation locations of the Dry Valleys. This lack of activity indicates the limits of life in terrestrial environments, carrying potential implications for life in extraterrestrial permafrost environments.



Over the Horizon

Climate change is having a profound effect on every part of the globe, but its effects are especially pronounced on the Earth's cryosphere. Readily observed and measured, the changes in snow and ice on land, glaciers, ice caps, and sea ice have long been evident. The effects on permafrost, however, are less conspicuous and have received less attention beyond the scientific community and Arctic residents. Nevertheless, permafrost is rapidly changing as a direct consequence of climate change, posing risks to Arctic peoples and the environment, and with significant implications for the entire planet.

The knowledge compiled in this atlas demonstrates how vital permafrost is for regulating the climate, maintaining unique ecosystems, supporting infrastructure, influencing hydrology, and sustaining the livelihoods of Indigenous communities.

- *Climate regulation and climate science:* Permafrost contains vast amounts of plant and animal matter, keeping them frozen for tens, even hundreds of thousands of years. When this organic matter thaws, it decomposes and releases carbon dioxide (CO_2) and methane (CH_4), both potent greenhouse gases. The release of these gases exacerbates global warming and climate change, contributing to a positive feedback loop that will last for centuries to come.
- *Health:* In addition to organic carbon, permafrost also stores contaminants. For example, permafrost soils store nearly twice as much mercury as all other soils, the ocean, and the atmosphere combined. As permafrost continues to thaw over the next century, this mercury becomes vulnerable to release into the environment. Other contaminants, including heavy metals, persistent organic pollutants, and microbiological agents, are also locked in permafrost, as long as it stays frozen. However, when the permafrost thaws, these pose a risk for both human and animal health.
- *Destabilisation and erosion:* Permafrost thaw dramatically destabilises the ground. Coastal communities see their shorelines crumble away, lakes suddenly drain, and infrastructure threatened. This destabilisation carries costs for human and animal health, the economy, and society. The costs for infrastructure damage alone could exceed USD 276 billion over the next 40 years.
- *Ecosystem services and biodiversity:* Specialised flora and fauna adapted to cold and frozen conditions make permafrost their home. These ecosystems provide a habitat for species that are uniquely adapted to permafrost environments and contribute to global biodiversity. As permafrost changes, lakes may drain and disappear, ice-rich coastlines erode, and tundra vegetation is replaced by shrubs and trees. These and other habitat changes can have serious consequences for the species dependent upon them.
- *Water resources and quality:* Permafrost plays a role in regulating regional hydrology. It can act as a barrier to water movement and influence the flow of rivers and streams. Some permafrost regions store significant amounts of fresh water in the form of ice. As permafrost thaws, it can release this water, potentially impacting local water resources, and even sea levels.
- *Indigenous communities:* Indigenous Peoples possess unique knowledge and cultural practices associated with permafrost environments, and changes in permafrost conditions can profoundly affect their ways of life. Understanding the impacts of ongoing change and determine the best adaptation strategies requires a respectful exchange between science practitioners and holders of local and traditional knowledge.
- *Earth's history:* Studying permafrost cores can provide insights into the past climate and provide information on the resilience of permafrost during warmer periods. This information can teach us about natural rates and consequences of change, unaffected by human agency.

Commonly, the social, physical, and health components of permafrost thaw have been studied in isolation, leading to inadequate policy options that ignore the holistic nature of the threat. For instance, contaminant release directly affects wildlife, which itself is harvested for food. Infrastructure failure directly threatens water and sanitation in communities, drastically impacting health and well-being. There is a need for an integrated and participatory approach to the complex issues at the nexus of climate change, permafrost thaw, infrastructure damage, contaminants, health and well-being, and for solutions founded on the cultural, natural, and social frameworks of local communities.

As climate change continues to affect permafrost regions, understanding and managing these ecosystems becomes increasingly important for the well-being of our planet and its inhabitants. This is also a time to rethink permafrost science, to foster co-design, and to share participation in observation, knowledge production, and their benefits. Some outstanding research topics are:

- Current projections of the impacts of permafrost thaw on the carbon cycle leave out important

processes and links. There is a need to incorporate the currently observed mobilisation of carbon on land and beneath the ocean into our models of change to better understand the multi-generational challenges of long-term feedbacks. Because permafrost thaw may trigger carbon loss that continues for centuries, these future emissions also need to be accounted for in modelling.
- Permafrost thaw, in its progressive and abrupt forms, will release pollutants, but the magnitude and the timing of the release remains unquantified.
- A new approach, including permafrost models projecting infrastructure lifetime into the twenty-second century, is needed to provide long-term vision and decision-making capacity to planners.
- There is a pressing need to evaluate the risks to wildlife and human health that result from changes in water quality due to permafrost thaw and to involve communities in developing nature-based solutions to improve their well-being.
- The interaction between human activities, climate change, and permafrost is creating numerous hazards which can have significant environmental, sociocultural, economic, and health-related impacts on Arctic communities. Greater effort is needed to develop adaptation, mitigation, and recovery measures that can be implemented in remote regions.
- A targeted effort to map out the interconnected impacts of permafrost thaw on One Health is needed to identify risks and to prevent and manage health risks in humans, animals, and our shared environment.
- Arctic Permafrost Ecosystem Services (APES) need to be identified and classified to underscore the global value of permafrost.

This atlas appears at a time when humanity's sense of permanence is uncertain. Human activity is pushing the limits of the planet to support us. It is in our best interest to preserve as much permafrost as possible. Achieving this requires a global societal transformation, breaking from our dependence on fossil fuels and reducing greenhouse gas emissions.

For those living on permafrost, urgent strategies are needed to cope with the ongoing changes. Once adapted to life on permafrost, people now face the need to adapt to a destabilised environment where homes, businesses, and transportation infrastructure are all at risk. Where permafrost has been actively relied on to restrict contaminants and pathogens, new solutions are required as permafrost thaw deepens and containment fails.

The most significant long-term impact of permafrost thaw for the global community is the substantial release of greenhouse gases for centuries to come, necessitating compensation by future generations. The duration and extent of this are still under investigation but from a permafrost perspective, current warming is already too much. Urgent action is needed to avert as much permafrost thaw as possible, and it is not too late if we act now. By significantly reducing our greenhouse gas emissions, we can protect the global climate from generations of uncontrollable permafrost emissions and work towards positive change for permafrost and the planet as a whole.

Glossary

Abrupt thaw – The rapid thaw of permafrost, usually by erosion, landslide or some other catastrophic process
Active layer – The top layer of permafrost soil that freezes and thaws
Active layer detachment slides – Slope failure(s) in permafrost areas, in which the active layer detaches from the frozen ground beneath and slides downslope
Aerobic – In the presence of oxygen, usually because air is available
Alaas – A depression or drained thaw lake typically covered by grasslands resulting from thawing of ice-rich permafrost
Anaerobic – In the absence of oxygen, usually because all oxygen has been consumed and air is not available
Arctic amplification – The phenomenon of faster warming in Arctic regions compared to the global average
Benthic – The bottom of a water body, such as an ocean, lake or river
Bioaccumulate – The gradual building up of a (harmful) chemical in an organism. In food chains, chemicals tend to become more highly concentrated in organisms higher up the chain
Carbon – The main element of life on Earth and the main element in greenhouse gases. It occurs in organic and inorganic compounds, mostly based on whether the carbon is bonded with hydrogen (as in most life-forms) or not (for example in minerals)
Carbon cycle – The movement of carbon between the different reservoirs (land, ocean, atmosphere) of the Earth
Carbon sequestration – The capturing and storing of carbon dioxide from the atmosphere
Carbon sink – Anything that absorbs and accumulates more carbon than it emits
Climate scenario – Results of computer modelling of the Earth's future climate that include estimates of future human greenhouse gas emissions. There are often called future "projections" or "pathways", and include low, moderate and high emission alternatives. Projections for future greenhouse gas emissions and their impacts on the climate, sometimes categorised into low/intermediate/high depending on the rate of temperature increase
Continuous permafrost – Permafrost that underlies 90 per cent or more of the ground in a region
Convection – A circular flow in gas or liquid that results from density differences, for example when warm water rises and cold water descends
Discontinuous permafrost – Permafrost that underlies 50-90 per cent of the ground in a region
Earth System Model – A computer model of the physical, chemical and biological processes of the Earth system
Erosion gullies – Trenches formed as soil material is washed away.
Positive feedback loop – A pair of processes, in which the result reinforces the cause
Frost heaving – The lifting of the ground surface during freezing
Glacial period – see definition for Last Glacial Maximum
Gradual thaw – The slow thawing of the permafrost by warming
Greenhouse gases – Chemicals in the atmosphere that absorb heat reflected from Earth's surface, trapping it and warming the atmosphere; the main greenhouse gases are water vapour, methane (CH_4, an organic compound) and carbon dioxide (CO_2, an inorganic carbon compound)
Ground subsidence – Sinking or a downward movement of Earth´s surface; in permafrost regions, subsidence can result from the thaw of ground ice
High Arctic – The northernmost part of the Arctic, defined by its climate and vegetation
Hydraulic conductivity – The relative ease of which a fluid can pass through soil or rock
Ice wedge – A body of ice that forms when vertical cracks open in the ground during winter and subsequently fill with spring meltwater. As the water freezes, a vertical vein of ice is created which becomes wider every year as the process repeats itself, typically widest at the top. If several ice wedges grow large enough, and join, they create ice wedge polygons
Interglacial period – A geological period during which warm air temperatures shrink glaciers and ice caps. An interglacial period usually comes between colder glacial periods during which the ice masses grow.
Isolated permafrost – Permafrost that underlies less than 10 per cent of the ground in a region
Last Glacial Maximum – The geological period during which glaciers were at their largest around 25,000 years ago
Linear infrastructure – Features built along a continuous line, such as roads, railways, utilidors and pipelines
Methanotrophic microbes – Microorganisms such as bacteria or archaea that use methane as their source of carbon and chemical energy
Negative feedback loop – A pair of processes, in which the result dampens the cause
Outburst flood – A sudden release of a large volume of water for example from a naturally dammed lake. Such floods are not frequent but can cause a lot of damage
Permafrost – Ground with a temperature at or below 0 °C for at least two consecutive years.
Pingo – Large, roughly conical hill with an ice core, covered with soil and vegetation
Point infrastructure – Built features that are not connected, such as an airport, drilling pad or harbour
Primary production – Creation of chemical energy for living organisms from inorganic substrate, for example via photosynthesis
Retrogressive thaw slumps – A permafrost landform caused by the thawing of ice-rich permafrost, leading to a slope collapse and retreating headwall
Rock glacier – A permafrost landform consisting of rock debris frozen in or on top of ice
Sporadic permafrost – Permafrost that underlies 10-50 per cent of the ground in a region
Talik – An area of unfrozen ground within permafrost
The Paris Agreement – An international treaty adopted in 2015 by 194 countries. The treaty has a long-term goal to keep the mean global temperature warming well below 2 °C above pre-industrial levels
Thermal abrasion – The destruction of frozen coastline by the mechanical and thermal action of waves
Thermal denudation – Erosion of shorelines caused by warming and thawing of permafrost above the water line
Thermokarst – Depressions in the landscape formed by permafrost thawing and ground ice melting, which lowers the ground surface (see ground subsidence). Such depressions may fill with water to form thermokarst ponds or lakes
Thermosyphon – A passive heat exchange device utilising convection to cool the ground
Turbidity – A measure of the relative clarity of a liquid
Yedoma – A carbon-rich and ice-rich class of permafrost deposits found in Siberia (Russia), and parts of Alaska (United States) and Yukon (Canada)
Zoonoses – Infectious diseases, also known as zoonotic diseases, that have jumped from animals to humans

Acronyms

ACD	Arctic Coastal Dynamics
ACE	Air Convection Embankment
ACPR	Arctic Circumpolar permafrost region
AMAP	Arctic Monitoring and Assessment Programme
APPVI	Arctic Permafrost Population Vulnerability Index
AR6	Sixth Assessment Report
CALM	Circumpolar Active Layer Monitoring
GRP	Global Regional Product
Gt	Gigaton (109 t, 1015 g) = a billion tonnes
GTN-P	Global Terrestrial Network for Permafrost
HKH	Hindu Kush Himalaya
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
NDVI	Normalised Difference Vegetation Index
NSIDC	National Snow and Ice Data Center
Pg	Petagram (1015 g) = a billion tonnes
POPs	Persistent organic pollutants
RCP	Representative Concentration Pathway
SDWG	Arctic Council's Sustainable Development Working Group
Tg	Teragram (1012 g) = a million tonnes
UNEP	United Natio ns Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization
WWF	World Wildlife Fund

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Earth's Freezer

Frozen grounds

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Awakening Giant

Warming up, warming down

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Disappearing act

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Holding Tight

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Europe's frozen heart

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NUNATARYUK

The Arctic Permafrost Atlas was written and edited by GRID-Arendal together with all NUNATARYUK project partners, scientists, and early-career scientists. It presents state-of-the-art knowledge about permafrost and the impacts of permafrost thaw on human settlements in the Arctic.

The Arctic Permafrost Atlas is a key deliverable of the NUNATARYUK project. NUNATARYUK is an international permafrost research project consisting of 26 partners from 14 countries working together to understand how thawing permafrost on land, along the coast and below the sea changes the global climate and life for people in the Arctic.

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ARTIST SPOTLIGHT

Olga Borjon-Privé (Oluko)

I was born and grew up on the Taimyr Peninsula, located in the Arctic part of Siberia. My mother was a teacher by profession and an artist at heart, and my father loved to draw. Thanks to him, I picked up a pencil and began to draw characters that I had invented or read about in books.

I studied at the Norilsk College of Arts and the State University of Saint Petersburg, where I received an artist diploma and a teacher's diploma of decorative and applied arts. I worked for three years at the Taimyr House of Popular Creativity and for 10 years as a teacher at the Norilsk College of Arts.

I use different materials and techniques to create my works. When I paint, I use acrylic. When creating graphic works, I use ink, watercolour, and soft materials like pastels or charcoal. For the illustrations for the Arctic Permafrost Atlas I used a graphics tablet, which allowed me to achieve a variety of effects thanks to a large selection of brushes. I am inspired by traditional folk art, folklore, history, and the people I meet. I'm also inspired by nature: landscapes, textures, and the animal world.

From the very beginning of this project, I worked with great enthusiasm to create illustrations for it. Although the people portrayed in the Atlas come from different parts of the Arctic, I understood their problems and feelings perfectly. The theme of permafrost is common to us – the people who live or are born there. Permafrost is an integral part of my homeland. To my people, the ground is like deerskin, the trees and plants like hairs, and the people like insects.

As I learned the stories of others who are experiencing environmental change, I became more deeply inspired by it and understood how important it is not to be silent about it. I wanted my illustrations to talk not only about the problems, but also tell readers about the place or culture of the people living in these regions. By studying the places, people, and the traditions mentioned in the texts, each illustration became an independent plot.

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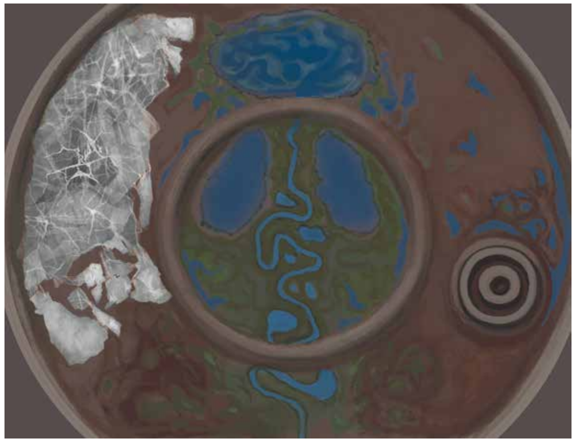
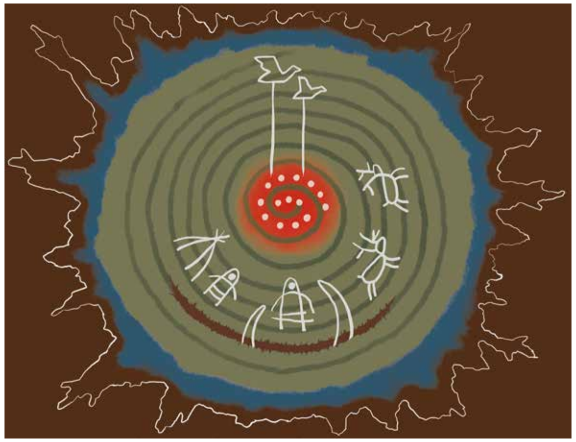
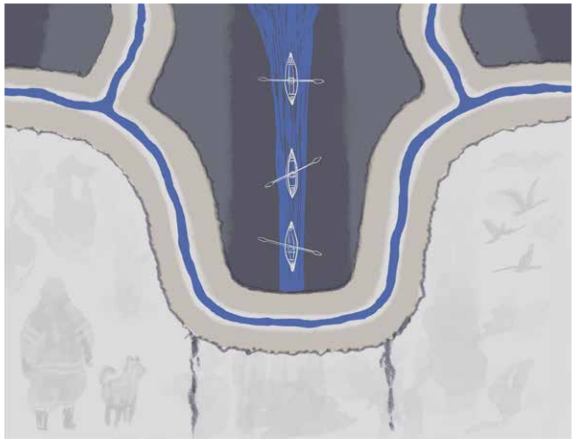


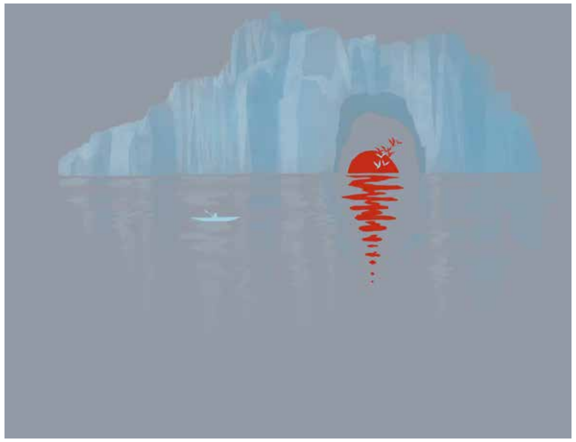
Scientists use maps to assess the consequences of both permafrost thaw and human activities. The threat to the environment is also hidden in landfills that arose from previous human industries: for instance, containers that contained fuels and lubricants are beginning to collapse. I have depicted the tundra in stains against the background of the rusty surface of an oil barrel. Numerous lakes are represented as human organs, and nature as a living organism.



This illustration is enclosed in a circle, in the form of a traditional Yakut calendar, which I took as the basis for creating the plot. The elements of the composition are located around the centre, the red colour symbolising the sun. Climate change entails changes in the traditional way of life of people: the number of fishers and hunters is decreasing, and more and more people are collecting mammoth tusks. In northern and eastern Siberian cultures, the mammoth has long been associated with evil or strong spirits who warn of danger.



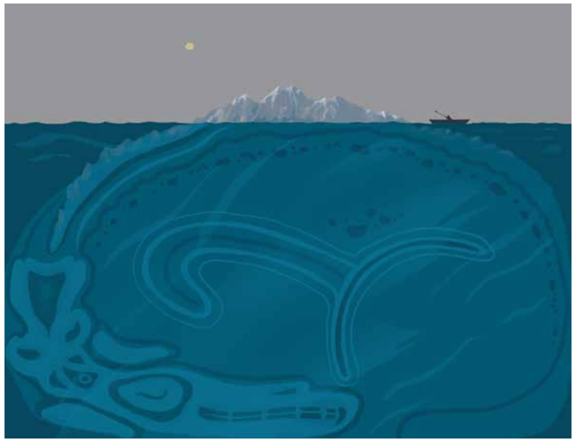
This illustration was inspired by a traditional Inuit parka. Its smooth lines and shapes suggested an outline in which I could depict the main elements of the composition. I have imagined a map on which I have placed mountains, rivers, fishing boats, roads, as well as silhouettes of a man with a dog and birds. This is part of the life of the inhabitants of Aklavik – their activities, their place. With the onslaught of warming, permafrost is retreating, exposing its pressure points, primarily through the state of infrastructure and then affecting the lifestyle of its inhabitants.



The thawing of permafrost due to global warming is a serious change that worries people living in the Arctic, as it affects their lifestyle and puts it at risk. This thawing occurs gradually, and since permafrost is underground, it is not very noticeable. However, the thawing of glaciers directly shows the process of climate change on Earth. In the illustration, I have tried to show the beauty of nature against the background of glaciers, an integral part of the Arctic landscape.

The accident next to Norilsk has served as the main plot for the creation of this illustration. I have drawn a tundra landscape in spring, in which I have imagined a river in the form of a bending deer. This river is depicted with an oil product that got into it because of an accident, and therefore the deer-river meanders as it suffers from torment. I have worked for many years in Norilsk. With sadness in my heart, I understand that this tragedy will have serious consequences for the entire ecosystem of my native land and for the dietary health of my people.

This illustration depicts the situation when, due to global warming, water occupies more and more space and pushes people out of their homes. At the centre of the composition is a man contemplating the house he has lost. The reflection of the sky on the water in the silhouette of the house corresponds to the man reflecting on his memories of the place he once lived.



"It surprised me how diverse permafrost is. It is sort of a living, breathing, moving creature." Suzanne compares permafrost with a living, breathing, moving creature. This became the main plot of my illustration. The philosophy of the local peoples, the main message of which is to live in harmony with the surrounding world, shows us that permafrost is the basis of life in the Arctic. I would like to show this idea of unity of humanity with nature and how much we depend on it.

The elements of this illustration are arranged so that together they depict an inuksuk. An inuksuk is a traditional Inuit stone monument, used as a landmark for travellers and installed in sacred places and burial sites. Permafrost is represented here in the form of a block of ice: a fragile basis for the life of local residents. The moon and stars against the background of the polar sky silently observe the changes that have already begun.

Ingrid's statement about the buildings in Ny-Ålesund inspired me to create this illustration. They open a window to the past and tell us about people's hopes and perseverance. Therefore, my main element is a pattern on a frozen window in the form of a flock of birds as a symbol of undying hope. I depicted coal houses in the background to convey that Ny-Ålesund was a mining settlement and, despite the fact that coal mining stopped, the houses there are kept in memory of this time.

ARTIST SPOTLIGHT

Katie Orlinsky

Photographer Katie Orlinsky has spent the last 15 years covering news stories and feature assignments around the world for publications like National Geographic, The New York Times, and The New Yorker. For the last eight years, the majority of her work has explored how the climate crisis is challenging and transforming the relationship between people, animals, and the land. Katie's photography has earned awards from World Press Photo, Pictures of the Year International, Alexia Foundation, Visa Pour L'image, PDN, and the Art Director's Club. She received a BA in Political Science from Colorado College and an MS in Journalism from Columbia University. Katie teaches as a visiting professor at New York University and the University of Alaska Fairbanks.

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After a successful hunt, a young Inupiat man takes a break from moving whale meat into his family's ice cellar in Utqiagvik, Alaska. Ice cellars are large underground freezers, often generations old, dug deep into the permafrost. However, as permafrost thaws, the cellars may become unusable, either physically damaged or warming to the point where it is no longer safe to store food.

Thawing permafrost beneath the earth's surface releases methane gas into Arctic lakes, causing gas bubbles to form in the frozen water. If the gas is released, a small flame can create a brief fire on the lake's surface, as demonstrated by Melanie Engram and Allen Bondo on a pond near Smith Lake in Fairbanks, Alaska.

The Batagaika crater near the Siberian town of Batagay in Russia has been called the "hell crater" or the "gateway to the underworld". Over 90 metres deep and one kilometre long, this thermokarst depression is one of the largest in the world, holding over 200,000 years of history and climate information. It started forming in the 1960s when the permafrost under the area began to thaw after nearby forests were cleared.

The village of Newtok, Alaska, is sinking as the permafrost beneath it thaws. On a summer bird hunt, four Yupik boys cross a flooded walkway. Newtok is the first community in Alaska to start relocating as a result of climate change, pioneering a process that many other Alaskan villages may soon undergo.

The permafrost tunnel near Fairbanks, Alaska, was built by the United States Army Corps of Engineers in the 1960s and is now used to research and study permafrost. The 110-metre-long tunnel walls contain soil, fossils, frozen animal and plant remains, silt, sand, gravel, bedrock, and thousands of years of history.

Animals graze in the Uvs region of Mongolia. In the winter of 2017–2018, extreme weather conditions in Uvs led to a natural disaster known locally as a dzud. Frigid winds from Siberia caused the temperature to drop to below −50 °C. More than 1 million animals froze or starved to death because they were unable to graze. As summers become hotter and drier, less hay is available for livestock to gain the weight they need to survive the harsh winters.

The Alatna River, Alaska. The treeline is the northernmost limit of where trees can grow. As a result of climate change, the treeline is moving north, transforming the tundra landscape and bringing new wildlife species, such as beavers, moose, and snowshoe hares into the Arctic. Scientists are only just beginning to understand what this means for the future, in particular what impact these landscape changes could have on accelerating permafrost thaw.

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