CASCADE INSTITUTE

PROTECTING **PERMAFROST**

Addressing the climate threat of Arctic thaw

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EXECUTIVE SUMMARY

Climate heating is disproportionately affecting northern regions, with average temperatures in Canada's North rising roughly four times faster than the global average. This heating is disrupting vast ecosystems across the Arctic and threatening the lives, livelihoods, and cultures of Northerners. It is also creating profound impacts below the surface, in ways that will accelerate, and may imperil, our efforts to limit further heating.

This is because surface warming is seeping into the *permafrost*—the massive deposits of long-frozen soil buried beneath the surface—causing the permafrost to thaw. Permafrost thaw changes the local landscape, for example by draining existing lakes or creating new ones (Wilcox et al., 2020), or by causing ground to shift, damaging roads, buildings, and other infrastructure.

Permafrost thaw also leads to significant releases of the heat-trapping gases that cause climate change, as the thawed organic material in the permafrost begins to decay. Such emissions are rapidly growing, as the warming climate thaws more and more permafrost. Permafrost regions are now releasing more carbon than they absorb (Natali et al., 2024; Noor, 2024). And as global temperatures rise, the rate at which permafrost releases carbon dioxide and methane will accelerate.

The vast amount of carbon locked up in permafrost—an estimated 1,500-1,700 gigatons, roughly twice the amount currently in the atmosphere—means that runaway permafrost thaw could eventually become a devastating emissions source. Such an outcome would seriously challenge efforts to keep atmospheric temperatures within a range that can support complex life as we know it.

Unlike emissions from fossil fuels or agricultural activity, which we can reduce or eliminate by switching to other energy sources or by changing agricultural practices, there is no simple fix for permafrost emissions. Once permafrost thaws, emissions will continue for centuries (*Country of Permafrost*, 2022)—an unstoppable climate-cooking cascade. Thus, even if we succeed in curtailing human-sourced climate pollution, the planet's temperature may continue rising, driven by a pernicious permafrost feedback loop.

> *There are ways for the North to take action, leveraging growing knowledge of the mechanisms causing permafrost thaw and emissions and emerging ideas of what can be done about these threats.*

However, there are ways for the North to take action, leveraging growing knowledge of the mechanisms causing permafrost thaw and emissions and emerging ideas of what can be done about these threats.

For example, recent work, summarized in this report, has identified 13 potential interventions that can slow or stop thaw and reduce or delay resulting emissions (Table A). These interventions would help preserve Arctic ecosystems and buy time for the world to reach net zero, arresting any further rise in temperature before permafrost thaw becomes unmanageable.

So far, only three of these interventions—wildfire management, caribou herding, and conservation or restoration of peatlands and wetlands—are already commonly practised, though not yet in ways designed to specifically prevent or slow permafrost thaw. Work on the other 10 is at very early stages. Intervention proponents will need to achieve significant advances if they are to be available in time to be useful.

Meanwhile, Northern rights holders, alongside scientists, practitioners, governments, and permafrost research institutes, are starting to think through the many political, legal, social, scientific, technological, and other issues associated with testing, deploying, and managing such interventions.

TABLE A:

Overview of the assessed interventions

UArctic ID	Intervention	Tech readiness	Scalability	Timeliness	Termination shock risk
1. Interventions with local impact					
44	Enhanced permafrost freezing with air pipes				
-	Snow compaction in winter			?	
-	Draining of thermokarst lakes/regions	?	?	?	
41	Conservation and restoration of peatlands and wetlands in taiga and tundra				
2. Interventions with regional impact					
37	Wildfire management				
39	Caribou herding				
40	Rewilding of permafrost regions				
-	Engineered methanotrophs		?	?	?
49	Methane flaring (not industrial)			?	
3. Interventions with global impact					
20	Arctic winter stratospheric aerosol injection				
21	Cirrus cloud thinning		?	?	
22	Mixed-phase regime cloud thinning		?	?	?
24	Space-based solar radiation management				

Summary of assessments for the 13 potential interventions discussed in the paper. See Section 3 for details.

Indeed, identifying effective interventions addresses only part of the challenge of permafrost thaw. Any program to reduce thaw and preserve Arctic ecosystems will need to advance five linked initiatives:

- **Improve understanding of the science of thaw and associated emissions.** To slow or stop thaw, we need to better understand and be able to predict how, where, and why thaw and the resulting emissions are happening.
- **Gather better data about permafrost regions.** Researchers need more and better long-term data to effectively answer questions related to thaw, emissions, and mitigation.
- **Develop high-quality permafrost thaw models.** Better models of the North can tell us where, when, and how thaw (and emissions) will happen, and where (and which) actions may be needed.
- **Craft thaw-mitigation and emissions-mitigation strategies.** Researchers will need to develop and test interventions that can slow or stop thaw and reduce or stop the consequent release of heat-trapping gasses. This work will take time, substantial resources, and deep community support.
- **Develop and deploy an operating model for governance and decision making.** All thaw mitigation work should be framed under a governance model that engages with and has the support of stakeholders, particularly local populations and communities.

Of course, these five initiatives are no substitute for global efforts to reduce the release of heat-trapping gases. Indeed, if we are unsuccessful at achieving such reductions, the resulting warming will eventually overwhelm the permafrost thaw interventions explored here.

Canada has more permafrost than any country but Russia and has the deep science-and-technology foundation and industrial base needed. And with strong working relationships with other Arctic nations, Canada is well-positioned to play a leadership role in a global effort to tackle this problem, for the benefit of all.

Indeed, given the current challenges in Russia and the United States, we feel Canada can take a global leadership role in permafrost emissions reduction work by spearheading the establishment of a global framework for measuring, monitoring, and mitigating permafrost thaw emissions.

Faced with this challenge and opportunity, the Canadian federal government, with the central involvement of Northern community leaders, should establish a permafrost thaw mitigation task force that brings together key Canadian political and community leaders, permafrost science experts, and other stakeholders to develop a permafrost thaw mitigation strategy. Such a task force could be chartered to come up with:

- a clear and compelling problem statement around the value of permafrost thaw mitigation to Canadians and the world, including desired outcomes;
- an assessment of key risks, opportunities, strengths, and gaps;
- a program governance model, including a strategy for stakeholder engagement;
- high-level goals, success metrics, and potential intermediate milestones; and
- an initial program budget, structure, and operating model.

Given the magnitude of the challenge, such a program will need to run over decades and will need to be adaptable to changing circumstances. It will thus be critical to have broad public support and a flexible operating model.

This report seeks to inform Canadian Northern community leaders and policymakers of the permafrost problem and of emerging ideas for addressing it. However, the analysis and recommendations presented here should apply to all permafrost countries and be of interest to any stakeholder trying to address permafrost thaw.

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1. Introduction

1.1 The permafrost carbon feedback problem

The research is conclusive that permafrost thaw[1] leads to the release of carbon dioxide and methane—carbon-based greenhouse gases that contribute to climate heating (Plaza et al., 2019). Current estimates suggest that permafrost contains, globally, on the order of 1,500-1,700 gigatons of carbon (Miner et al., 2022; Schuur et al., 2015), roughly double the 850 gigatons currently in the atmosphere. Large-scale thawing of permafrost would add large amounts of carbon into the atmosphere and could, over time, become a dominant contributor to climate heating.

> *Over the past 20 years, permafrost regions have turned from being net sinks of atmospheric carbon to net sources.*

Until recently, research calculations reported by the Intergovernmental Panel on Climate Change (IPCC) suggested that permafrost thaw would accelerate as the planet warms, but is likely to remain a small contributor to greenhouse gas emissions in this century (Intergovernmental Panel on Climate Change, 2021). Consequently, IPCC targets for carbon emissions reduction have largely ignored permafrost thaw, under the assumption that we can slow and arrest warming through other mitigation activities before thaw becomes a concern.

More recent research, however, puts these assumptions in doubt.

First, observational studies have confirmed that permafrost is thawing more rapidly than 20 years ago, and that in that time, permafrost regions have turned from being net sinks (absorbers) of atmospheric carbon to net sources (Luhn, 2024.; Natali et al., 2019; Natali et al., 2024; Noor, 2024). Second, Arctic regions are now known to be warming up to four times faster than the global average (Rantanen et al., 2022). This *Arctic amplification* (see Appendix 1) will significantly accelerate permafrost thaw. Third, research has identified non-linear rapid thaw mechanisms (Schuur et al., 2022) that threaten to further accelerate the rate of permafrost thaw and the release of carbon dioxide and methane as temperatures rise.[2]

1 In the literature on permafrost, the term *permafrost thaw* typically refers to both thawing of permafrost and the impact of such thaw, such as landscape (e.g. land slumps, lake formation, coastal erosion, landslides) and ecosystem changes, and emissions of carbon dioxide and methane. Because of this, some authors prefer the term *permafrost degradation* to reflect these wide-ranging impacts.

2 Carbon dioxide and methane are by far the most significant heat-trapping gases released when permafrost thaws, and so are the focus of this report. In some cases, though, an additional heat-trapping gas, nitrous oxide, can also be released. All three gases will need to be considered in a program targeting emissions reduction from permafrost thaw.

Other work has highlighted that, once permafrost thaws, decomposition and resulting emissions will likely continue for centuries (*Country of Permafrost*, 2022). This means that, once sufficient permafrost is thawed, we are locked in for a century or more of likely unstoppable climate heating.

> *Averting climate disaster will likely require even more aggressive emissions reductions, including targets to reduce emissions from permafrost thaw.*

This combination of factors suggests a future in which permafrost carbon is being released into the atmosphere sooner and in larger quantities than current models suggest, causing faster and more extreme global heating than predicted in today's scenarios (Natali et al., 2021). Consequently, there are growing calls for more considered incorporation of permafrost carbon processes into Earth system climate models (Natali et al., 2021; Schädel et al., 2024), particularly in the next IPCC assessment and recommendations, due in 2027.

The real-world implications of this need to recalibrate our climate models are dire. The world is already exceeding emissions targets (Boehm et al., 2023; The Economist, 2022) that would keep us below the IPCC's climate heating red line of 1.5°C above pre-industrial levels (Intergovernmental Panel on Climate Change 2022).[3] And accelerating but uncounted emissions from permafrost will put the world further off track. Averting climate disaster will likely require even more aggressive emissions reductions, including targets to reduce emissions from permafrost thaw.

With roughly 50 per cent of Canada's land surface underlain by permafrost (Stuart A. Harris, 2010), any call to directly target permafrost emissions reductions will fall substantially on Canada. Therefore, Canada needs to better understand the scope and scale of permafrost thaw—and needs to develop and begin implementing realistic plans for tackling thaw emissions.

While the threat is dire, many unknowns remain. We can say with confidence that emissions from permafrost thaw will continue to grow. But we don't know how quickly the rate of thaw will accelerate, nor do we know which interventions would most effectively slow or reverse this acceleration.

3 In 2024, the world's global average temperature rise exceeded this 1.5°C target for the first time (World Meteorological Organization, 2025b). While global temperatures would have to remain above this threshold for several years before climate scientists would consider the threshold definitively breached, the alarming rise over the past couple of years underscores the urgency of dramatically reducing the release of further heat-trapping gasses into the atmosphere.

As a starting point, Canada needs to better understand the processes driving permafrost thaw and the consequent release of carbon dioxide and methane, so we can better predict what's coming. Second, Canada needs to develop and demonstrate practical ways to slow or stop permafrost thaw and carbon dioxide and methane release. Third, Canada needs to develop a way to govern, operate, and fund the coordination of response measures that engage all parties impacted by this challenge. And finally, Canada must align these efforts with those underway in other permafrost nations—Russia, China, Mongolia, the United States, Greenland, and the Nordic countries.

1.2 Global stakes, Northern decisions

Permafrost carbon feedback, permafrost thaw, and the resulting carbon dioxide and methane emissions are clear threats to the global climate and to human well-being. But while the stakes are global, both the threat of continued permafrost thaw and the risks associated with some of the measures that seek to arrest it are profound and specific to the Arctic and Sub-Arctic. These regions are majority Indigenous and face a deep infrastructure disparity compared to the rest of Canada. Any discussion of interventions must be grounded in the reality that many of these communities exist on unceded, treaty, and self-governed lands, and any interventions must be led by the Indigenous Peoples who steward life in the region.

For Northerners, the threat of permafrost thaw goes far beyond the release of heat-trapping gases. Permafrost thaw destabilizes critical infrastructure such as homes, bridges, roads, and essential supply routes. Permafrost thaw also disrupts access to—and indeed the very integrity of—hunting lands and other resources that are vital to local economies and traditional ways of life (Firelight Research Inc. with the Canadian Climate Institute, 2022).

This report focuses on ways to limit the release of heat-trapping gases from thawing permafrost. However, the consequences of both thaw and thaw interventions for Northern communities and Indigenous Peoples must be the main focus of any analysis and response. Other research groups like Permafrost Pathways (a collaborative initiative between Woodwell Climate Research Center, the Arctic Initiative at Harvard Kennedy School, and the Alaska Institute for Justice) are pursuing both tracks in parallel, highlighting the need for integrated approaches that balance research on carbon dioxide and methane emissions with local needs and priorities.

Northern Indigenous Peoples have endured a long and brutal history of external actors (including governments, resource extraction companies, universities, and research organizations) conducting experiments and imposing interventions—

whether social, economic, or technological—on their lands and in their communities. Given this legacy of harm and the profound consequences on Northern lives and livelihoods that interventions could entail, Indigenous Peoples must have significant decision-making authority regarding the prioritization, evaluation, and adoption of thaw mitigation strategies. The development of partnerships between Northern Indigenous Peoples and external actors should be aligned with the United Nations Declaration on the Rights of Indigenous Peoples and frameworks like the First Nations Principles of OCAP (ownership, control, access, and possession), the latter of which protects Indigenous data sovereignty in research and decision making (First Nations Information Governance Centre, n.d.).

> *This report is a primer for stakeholders grappling with the permafrost carbon issue from a solutions perspective.*

Beyond deciding whether and which research, pilot projects, and mitigation strategies should proceed, Northern Indigenous Peoples should also be the ones defining the parameters for assessing possible intervention strategies, since the evaluation of the desirability, feasibility, and potential risk of interventions is a deeply relational and subjective process infused with value judgments. Northern Indigenous Peoples should also take the lead in evaluating, prioritizing, and implementing interventions. The University of the Arctic's intervention compendium (Alfthan et al., 2023), which looks broadly at interventions that could address climate impacts in the Arctic (including permafrost thaw), also advocates for centring Northern voices in the conversation around climate interventions.

The *Protecting Permafrost* report was reviewed by Northern Indigenous community leaders and experts, but does not necessarily speak to the assessments or priorities of those individuals or communities. Rather, this report seeks to provide Northern Indigenous Peoples, policymakers, and relevant research communities with a concise summary of the permafrost carbon feedback problem, a thorough scan of plausible intervention strategies, and a preliminary assessment of the desirability, feasibility, and potential risk of those interventions. This report is a primer for stakeholders grappling with the permafrost carbon issue from a solutions perspective. It sets the stage for more participatory conversations around the interventions it presents.

1.3 Structure of the report

Section 2 summarizes the properties and attributes of permafrost and permafrost regions under warming conditions. This is the foundation from which we can begin to assess how potential interventions might slow emissions or thaw.

Section 3 considers 13 interventions that may be effective in preventing or slowing permafrost thaw and the consequent release of carbon dioxide and methane. So far, most of these interventions are just ideas: substantial, sustained work will be needed to test and prove their efficacy, and to understand where and how they might be useful.

Given that development and deployment of interventions will likely require review of existing (or missing) regulatory and governance frameworks, and detailed policy recommendations, we also note where proposed interventions may be subject to existing national and international regulations and agreements, such as around ozone layer protection or transboundary air pollution. Appropriate attention to this issue will also require continuous engagement with leadership from Northern and Indigenous communities and governments.

Section 4 concludes by proposing a framework for a permafrost thaw management plan, built on the elements needed for success: the ability to effectively monitor permafrost thaw and emissions; the ability to monitor and measure the impact and effectiveness of interventions; and appropriate engagement with and support of local governments and communities, particularly the Indigenous Peoples who live in the regions that both permafrost thaw and interventions to slow it will impact.

This analysis is preliminary. But current evidence strongly suggests that accelerating permafrost thaw presents a significant risk both to the global climate and to the well-being and livelihood of communities in the North. We believe it is essential to start acting on this risk, before the relentless acceleration of thaw overtakes our opportunity to change the trajectory of climate heating and avert the worst potential outcomes.

2. Background

2.1 Permafrost overview

PERMAFROST: KEY FACTS

- Permafrost is coolest near the surface, and gets warmer going deeper.
- Permafrost thaw is driven directly by rising surface temperatures, and indirectly by changes in precipitation, cloud cover, plant growth, and other consequences of climate change.
- Permafrost composition and structure can vary greatly from place to place, and with depth.
- Permafrost thaw can be gradual, or it can be abrupt and nonlinear.
- Gradual thaw is leading to increased annual emissions of the greenhouse gas carbon dioxide.
- Nonlinear thaw emits both carbon dioxide and methane—a far more potent greenhouse gas.
- Rising temperatures are leading to a rapid increase in the amount of nonlinear thaw.
- Per unit area, the climate impact of abrupt thaw is significantly worse—between one and three orders of magnitude worse—than gradual thaw.

Soil that remains frozen year-round, commonly known as *permafrost,*[4] extends over a large portion of Earth's land surface. Around 11 percent globally and roughly 15 percent of the northern hemisphere are underlain by permafrost (Obu, 2021).

Permafrost remains frozen due to low average surface temperatures: summer simply isn't warm enough or long enough to thaw more than a shallow layer of the surface. And once frozen, permafrost can remain so for a long time. Indeed, radiological dating finds some permafrost to be hundreds of thousands of years old (Froese et al., 2008), formed during the Pleistocene epoch of the great ice ages (from 2.6 million to 11,700 years ago). Permafrost layers can also be very thick—in some places more than a kilometre deep. And the soil in permafrost

4 Permafrost is defined as soil frozen for a minimum of two years. Formally, it represents a thermal state of soil, and not a soil type.

stores vast amounts of carbon in the organic material (plant, animal, and bacterial) that has accumulated over many tens of thousands of years, removed from the atmosphere through biological processes and then frozen. With twice as much carbon stored in permafrost as in the Earth's atmosphere, the climate is thus at significant risk of dramatic heating if the soil should thaw.

Geographically, *permafrost regions*[5] are mainly found in northern Eurasia (Russia, the Tibetan Plateau), northern North America (Canada and Alaska), Greenland, and the Nordic countries.[6] Smaller regions are also found in high-mountain areas such as in the Rockies, the Mongolian Plateau, and the southern Andes.

Permafrost is also found under the massive Antarctic and Greenland ice sheets and under the seabed in Arctic and Antarctic coastal ocean areas. This paper does not address these regions of submerged permafrost: thawing of this material also poses climate risks, but on much longer timescales (many thousands of years) as it is protected by the thick ice above it.

Most permafrost is in the Arctic, an area warming roughly four times faster than the planetary average (see Appendix 1). Thus, if we need to slow permafrost thaw to rein in climate change, interventions will be focused on Northern geographies and nations. For Canada, where permafrost underlies around 50 percent of our land surface, this will impact every province and territory except Prince Edward Island, New Brunswick, and Nova Scotia (Figure 1).

5 The term *permafrost region* reflects the fact that permafrost may not always be continuous in an area. For example, there are large regions of permafrost where less than 10 percent of the land has permafrost—regions with small permafrost islands in an otherwise permafrost-free landscape.

6 Most permafrost is found in Russia, with Canada second, and China third.

FIGURE 1:
Half of Canada's land mass consists of permafrost regions

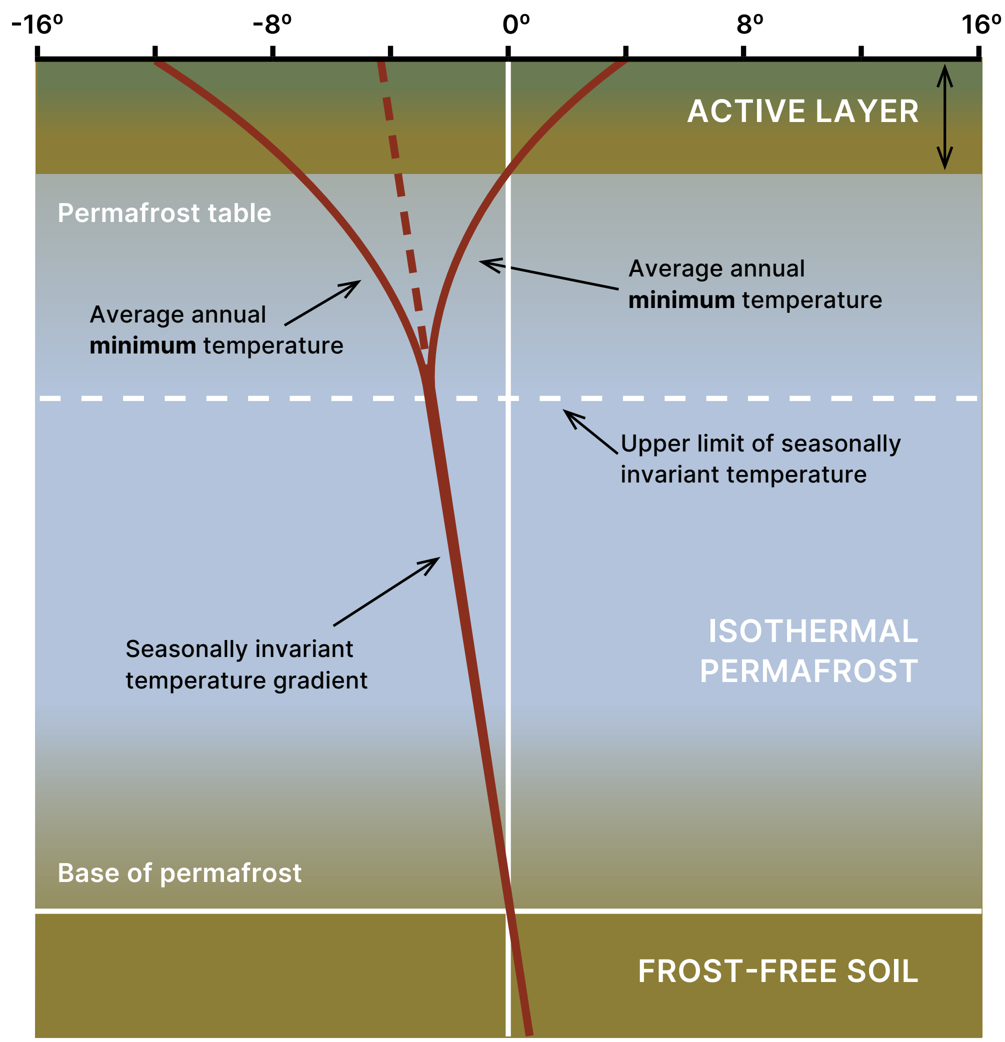
A map of Canada showing regions underlain by permafrost. Region names correspond to the percentage of surface terrain underlain by permafrost: continuous = 90-100 percent; discontinuous = 50-90 percent; sporadic = 10-50 percent; isolated = 0-10 percent), while "subsea" means the permafrost is below the seabed and under the ocean. Over half of Canada's land surface lies in a permafrost region, but only 40-50 percent of Canada's land surface is directly above permafrost, as permafrost is not continuous in any permafrost region. Source: adapted from Heginbottom et al. (1995), retrieved from Canadian Permafrost Association, n.d. Not covered by CC BY 4.0.

The surface and below-ground details of permafrost regions vary greatly from place to place, depending on factors such as surface topography, local climate and geology, the impact of water and erosion, and the history of how the landscape and the permafrost in it was formed. However, the basic ideas behind why permafrost exists, how it thaws, and how it releases carbon can be explained using a simple, idealized permafrost model.

Figure 2 shows an idealized vertical cross-section of a permafrost area, focusing on the layered ground structure and temperature profile with depth. At the top lies a layer of soil, known as the *active layer*, with the *permafrost* layer below. The red lines chart the temperature profile down through these layers. The leftmost line shows the lowest annual temperature (in other words, the coldest temperature in winter, averaged over multiple years). The rightmost shows the highest average annual temperature in summer. The dashed red line shows the temperature averaged over the year.

FIGURE 2:

A permafrost temperature profile—coldest at the surface and warming with depth



An idealized temperature profile of permafrost, as a function of depth. The leftmost red line charts the coldest winter temperature profile as a function of depth, while the rightmost line shows the profile at peak summer temperatures. The dashed red line shows the temperature as a function of depth averaged over a year. Note that the active layer thaws in the summer and freezes in the winter. The *permafrost table* denotes the boundary between the active layer (above) and the permafrost. Immediately below this table, the permafrost temperature varies during the year due to the influence of heat flow to and from the surface. But this influence decreases with depth: below the dashed black line, the permafrost temperature at a given depth stays the same throughout the year, rising slowly with greater depth due to geothermal heat rising from deep below. The permafrost layer ends where the temperature hits 0 °C: ground below this point is unfrozen. Source: adapted from “HylgeriaK”, 2014.

Active layer soil thaws in summer and freezes in winter: the range between the two red lines shows how the soil temperature varies through an average year. This layer is biologically active when thawed and serves as the foundation of the local ecosystem, supporting plant growth, animal activity, and other life. The permafrost below is biologically inert: bacteria or other life in the layer is frozen and inactive, while roots simply don't penetrate the permafrost, as they can't grow through frozen ground.

As in soil in temperate climates, biological activity in the active layer sequesters carbon into the soil. This happens in the summer as plants grow, accumulate carbon, and drop debris to the ground, which is degraded and incorporated into the soil. Bacteria in the soil release some of the organic carbon back into the atmosphere, mostly as carbon dioxide. But if the soil freezes, the carbon is trapped—sequestered—until it thaws again. The competing processes of carbon sequestration and release are key mechanisms of the permafrost carbon cycle, with the total amount of carbon released or sequestered each year being determined by the balance of these two processes.

Active layer soil structure, composition, and thickness vary greatly from place to place. Thickness, for example, can range from less than five centimetres to as much as 20 metres (Dobiński, 2020). This variation is due to factors such as local geography (hilly, flat, rocky), average surface temperature (active layers tend to be thicker where it is warmer), local rainfall, soil humidity, depth of winter snow cover, features of the landscape (shaded or sunny, hilly or flat, forested or low brush), and soil composition (sandy or gravelly soils tend to be deeper than those containing lots of clay or loam).

Compared with a thin layer, a thicker active layer can in principle support larger and more diverse plant species, including trees, requiring deeper root systems. Soil conditions (sandy or gravelly, loam versus clay-rich, humid, or dry) and local weather and climate influence which species flourish.

Permafrost lies below the active layer, with the *permafrost table* marking the boundary between them. Permafrost begins at the depth where the maximum (summer) temperature is at the freezing point, 0 °C. Below this, there is a range of depths over which the temperature varies seasonally while staying below 0 °C. The dashed horizontal black line marks the depth at which this variation ceases, below which the temperature at a given depth is constant throughout the year.

Permafrost is *coldest* at the top, adjacent to the active layer, with temperatures rising slowly until it hits 0 °C. Below this base, the temperature is above 0 °C, and any soil present is frost-free.

This vertical temperature profile—warmer at the bottom and cooler at the top—is a consequence of heat flowing up from the (warmer) earth below,[7] through the permafrost and active layers, and out into the (on average colder) environment above. In the absence of a changing climate, the average temperature profile is essentially a straight line as a function of depth: heat flow is constant through the layers, so the active layer, the permafrost, and the soil below it are each at thermal equilibrium.

Such a system will remain at equilibrium if three things stay unchanged: the heat flowing in at the bottom, the heat flowing out into the atmosphere at the top, and the thermal conductivity (a measure of how well heat is conducted) through the layers.

Climate change has broken this balance by raising the average surface temperature and reducing heat flow from the active layer into the atmosphere. This has pushed the entire system out of balance, and caused the ground to heat up.

To see why, consider what a warmer surface environment does. In winter, warmer surface temperatures reduce the differential between the atmosphere and the ground, reducing the rate at which heat flows from the ground into the air. In summer, warmer surface temperatures increase the rate at which heat flows into the ground. The result is less ground cooling in winter, more ground heating in summer—the ground, on average, gets warmer.

This change in heat flow eventually thaws the upper portion of the permafrost, adding material to the active layer and thinning the permafrost as the permafrost table recedes deeper. This thaw increases the soil material available for organic decay, which can lead to increased release of carbon dioxide and methane from the active layer.

The above description of thawing permafrost is often called the *gradual thaw* model since it assumes climate warming causes gradual thinning of the permafrost and thickening of the active layer. Quantitative versions of this model are known to accurately describe current conditions and forecast near-future thaw in regions experiencing gradual thaw. Such an approach was thus used in the 2021 IPCC assessments to forecast likely impacts of permafrost thaw and carbon emissions out to the year 2100. These forecasts suggest the rate of thaw will increase significantly as warming increases, and that every additional 1°C in climate heating relative to the 1850-1900 baseline temperature will lead to a roughly 25 percent reduction in the global volume of near-surface (down to 3 metres deep) permafrost (Arias et al., 2021, p. 76) by the year 2100, and to the release of between three and 41 gigatons of carbon (Arias et al., 2021, p. 97).

7 The geothermal energy flow from below is an inherent property of the Earth and is unaffected by climate change.

This seems like a lot of carbon, but it's actually a fraction of the amount expected to be released from burning fossil fuels over the same period. As a result, the most recent IPCC assessments do not flag permafrost thaw as a significant near-term climate change risk.

However, the last IPCC report came with an important caveat: our understanding of thaw is limited, and this assessment likely underestimates thaw emissions. In particular, it turns out that not all thaw is gradual. There are other thaw processes that can be abrupt and non-linear, leading to sudden and deeply penetrating thaw in relatively short amounts of time (in 't Zandt et al., 2020; Walter Anthony et al., 2018), with associated large releases of greenhouse gases.

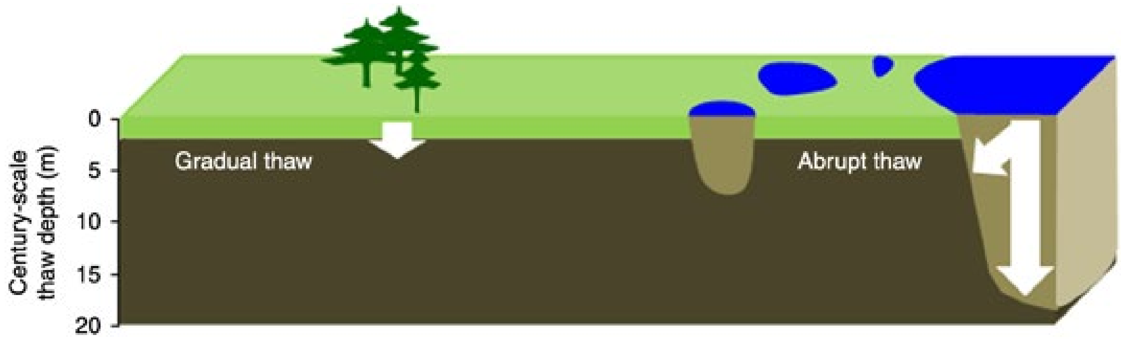
Moreover, in addition to releasing carbon dioxide, abrupt thaw can also release methane, a greenhouse gas with roughly 30 times the heat-trapping power of carbon dioxide, and sometimes also nitrous oxide, a gas with roughly 250 times carbon dioxide's climate impact.

Figure 3 contrasts the different physical properties of gradual and abrupt thaw: gradual thaw (left) slowly deepens the active layer, while abrupt thaw (right) can swiftly and fundamentally alter the local landscape. It can quickly thaw permafrost tens of metres or more down, exposing large amounts of thawed organic material to organic decomposition.

A *thermokarst landscape* is one well-understood pathway to abrupt thaw. This type of landscape occurs when ground ice melts in regions containing ice-rich permafrost, a phenomenon becoming more common as the Earth warms. In this landscape, thaw initially causes uneven ground settling, resulting in the formation of small pits, mounds, sinkholes, bogs, and lakes. The presence of groundwater (which is an excellent conductor of heat) enormously accelerates thaw, leading to the formation of even larger lakes and of *taliks*—domains of unfrozen soil that can extend deep down and outwards into, and even below, the surrounding permafrost. These taliks can quickly deepen and expand as the fluid in them accelerates heat flow out into the surrounding permafrost.

FIGURE 3:

Warming lake water can trigger abrupt thaw events

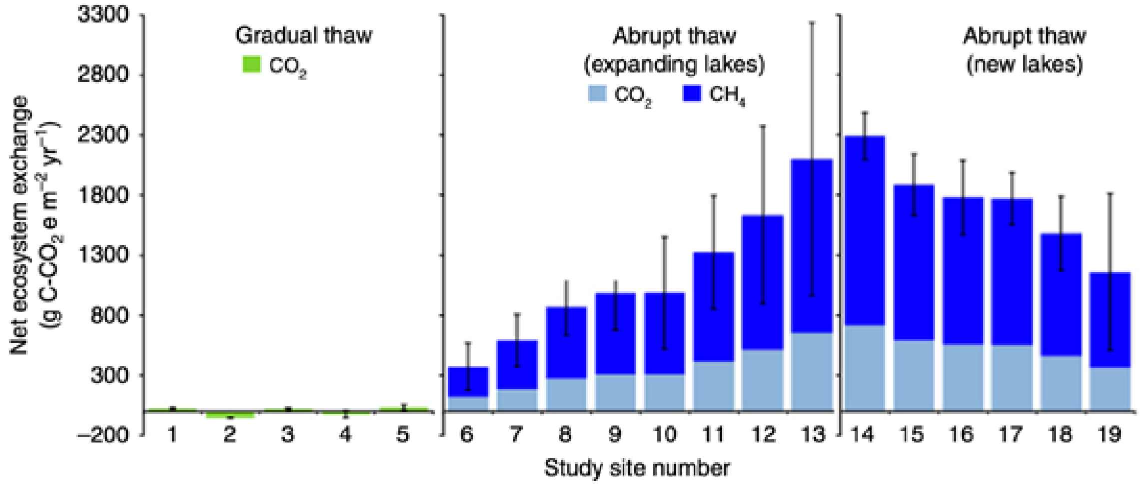


A simple schematic illustrating the difference between gradual, top-down thaw (left) and abrupt thaw beneath a thermokarst landscape (right). Source: Walter Anthony et al., 2018. Not covered by CC BY 4.0.

Figure 4 illustrates the enormous difference in emissions between regions undergoing gradual and abrupt thaws. This figure shows carbon exchange data (a measure of annual carbon emitted minus carbon absorbed due to sequestration) for regions experiencing gradual thaw (left) and regions undergoing abrupt, non-linear thaw (right). Note that an abrupt thaw emits orders of magnitude more greenhouse gas per unit area than a gradual. Also, carbon dioxide is essentially the only gas emitted from gradual thaw, whereas more harmful methane emissions are a significant component of abrupt thaw. The result is that, per unit area, abrupt thaw has a climate heating impact *10 to 1,000 times* greater than gradual thaw.

FIGURE 4:

Abrupt thaw events release orders of magnitude more heat-trapping gases than gradual thaw



Measured annual carbon emissions from study site areas experiencing gradual (left) and abrupt (right) thaw. The emissions from a gradual thaw are smaller, consisting mostly of carbon dioxide emissions, while in regions of abrupt thaw, the amounts are between 10 and 1,000 times larger, with methane emissions playing a significant role. Source: Walter Anthony et al., 2018. Not covered by CC BY 4.0.

> *In a worst-case scenario, nonlinear thaw could accelerate to the point where emissions from thaw are themselves sufficient to push global temperatures higher, even if all other human-caused carbon emissions were eliminated.*

There is also now evidence that climate change is increasing the number and magnitude of abrupt thaw events, leading to concern that abrupt thaw could become a dominant source of emissions as permafrost regions are pushed further away from thermal equilibrium (Yi et al., 2025).

In a worst-case scenario, nonlinear thaw could accelerate to the point where emissions from thaw are themselves sufficient to push global temperatures higher, even if all other human-caused carbon emissions were eliminated. If this were to happen, the only way to stop the rise in temperature would be to construct massive direct air capture technologies to remove carbon faster than it is being released, and/or to employ climate engineering to actively cool the planet. Removing enough carbon from the atmosphere to arrest runaway warming while simultaneously dealing with the consequences of that warming would be difficult, to put it mildly. And the potentially devastating consequences of climate engineering are hotly contested and still not well understood (National Academies of Sciences, Engineering, and Medicine, 2021).

To be clear, permafrost scientists do not believe that such a *permafrost carbon feedback* climate tipping point is imminent (Nitzbon et al., 2024), and do not yet have good estimates for the future rate of increase in rapid thaw events. But they agree that there is no safe level of permafrost thaw, owing both to the destructive impact of thaw on the landscape of the North, and to the fact that permafrost carbon emissions will require ever greater emissions reductions—and perhaps active carbon removal—elsewhere to stabilize the climate (Nitzbon et al., 2024).

2.2 Connecting thaw to interventions: Indicators, pathways, and mechanisms

The challenge before us is to determine how best to slow permafrost thaw and the resulting emissions of heat-trapping gases. But to meet this challenge, we need to know where and when thaw will happen and the likely severity of the resulting emissions, so that appropriate interventions can be applied at the right places at the right times.

This resembles the challenge of reducing the risk of floods or forest fires as the climate gets hotter, which is only possible if we can predict the risks and likely effects of fire or flooding. With accurate forecasting, a risk management program can deploy interventions: build dams or retention ponds, thin forest undergrowth, divert construction from high-risk areas, and so on. For permafrost thaw, such forecasting requires accurate and detailed models for the thermal and physical behaviour and properties of permafrost regions.

Scientists think that achieving this level of model accuracy is possible if we can gather enough information about permafrost regions, including the depth and density of existing permafrost ice and organic material, temperature profiles, topography and surface water, and weather and climate patterns. Indeed, the linear thaw models described earlier are good early examples of such models. But more complete data and more sophisticated models will be needed to cover the complete Northern landscape and the many different linear and nonlinear thaw mechanisms at sufficient granularity to deliver accurate forecasting that can inform interventions.

Such models will also require rich data characterizing the permafrost landscape over time, as such information can inform us of what is happening beneath the surface. Examples of such data—much of which can be gathered by land- or satellite-based remote sensing technologies—include expansion or contraction of wetlands, changes in ground temperature or snowfall, topographic changes, emergence of new taliks or bogs, or changes in ground elevation, which are collectively known to be indicators of changing permafrost state and potential future thaw (Devoie et al., 2021). See Appendix 3 for a more complete list of potential indicators.

Gathering such data over time, and leveraging sophisticated statistical and machine learning tools to interpret the information accurately, should reveal the regions at elevated or imminent risk of both abrupt and gradual thaw (Fatolahzadeh Gheysari & Maghoul, 2024; Howard, 2023), and give us the ability to deliver an effective thaw-and-emissions-reduction program.

Developing, testing, and proving this capability will be foundational to any thaw mitigation program.

In our case, thaw forecasting is only useful if it can be paired with interventions able to reduce the quantity or impact of future emissions. There are three conceptual pathways for achieving these reductions, which can be pursued via four types of intervention mechanisms:

<table>
<tr><th>Conceptual pathways</th><th>Practical mechanisms</th></tr>
<tr><td>1. Slow or stop thaw by reducing warming (reduce the rate at which organic material becomes available for decomposition)</td><td>A. Reduce the amount of incoming solar radiation to reduce surface temperature
B. Improve heat flow from the ground into the environment (better ground cooling)</td></tr>
<tr><td>2. Slow the rate of organic decomposition</td><td rowspan="2">C. Modify the environment in which emissions are generated (e.g. remove water, add oxygen)
D. Encourage or introduce bacteria, plants, or other changes that decrease rates of decomposition, or that modify decomposition pathways</td></tr>
<tr><td>3. Reduce methane (or nitrous oxide) emissions in favour of increased release of carbon dioxide (make the emissions less impactful on the climate)</td></tr>
</table>

The next section summarizes the 13 potential interventions, which tackle the problem using all four of these identified mechanisms. In many cases, they do so indirectly, by modifying aspects of the environment (such as snow cover, plant growth, or water level) to indirectly improve ground cooling, slow organic decomposition, or both.

3. Interventions to slow or prevent permafrost thaw and emissions

This section reviews potential permafrost thaw interventions—that is, interventions that can be applied directly in permafrost regions. Our starting point is a compendium, prepared by the University of the Arctic, of 61 interventions with the potential to slow, halt, or reverse the effects of global warming across all Arctic and northern regions, or globally (Alfthan et al., 2023). The compendium's interventions range from ones that are essentially global (such as orbital solar sunshades to reduce solar energy reaching the Earth) to ones that are intrinsically local, such as direct air carbon dioxide capture and storage. The compendium also includes many interventions tied to specific natural or ecological regions, such as oceans, ocean ice, glaciers, or permafrost.

This paper focuses on interventions that can be applied directly in permafrost regions. These interventions would directly cool permafrost or otherwise slow or stop permafrost thaw, or they could reduce greenhouse gas emissions from thawing permafrost. Development, deployment, and management of such direct interventions would fall to the countries (Canada in our case) and local communities where they would be applied. But because everyone on Earth has a stake in limiting the release of permafrost carbon dioxide, methane, and nitrous oxide, it will be important to openly share learning and experience with others tackling the same problems. Indeed, success will require many local efforts towards a global goal.

We also focus on interventions that can be deployed broadly across the natural permafrost environment, as opposed to ones specific to built infrastructure such as roads, towns, cities, or industrial facilities. There are, of course, some overlaps: for example, ground cooling thermosyphons are a common cooling technology for built infrastructure that can potentially be used across wide regions of permafrost.

The compendium describes 10 interventions that can be targeted at permafrost regions. We have independently identified three other potential interventions—snow compaction, draining of thermokarst lakes, and engineered methanotrophs—for a total of 13.

Details of the interventions and analysis follow, but can be summarized thus:

- There is no magic bullet. Slowing permafrost thaw and averting abrupt thaw events will likely require a portfolio of interventions that work in complementary ways.
- Of the 13 identified interventions, only three—wildfire management, caribou herding, and conservation or restoration of peatlands and wetlands—are close to being ready for wide use, and only one (caribou herding) may be applicable across all permafrost regions.
- The remaining 10 interventions require substantial and long-term research and development to be validated as deployable tools.

We group the interventions into three categories: those whose impacts are primarily local; those that would entail regional impacts, such as wildfire management; and those with potential international or global impacts, such as stratospheric aerosol injection.

The preamble in each section describes features common to interventions in the category. Where relevant, the preamble also describes existing and relevant international, regional, or local governance and regulatory structures.

Our intervention discussions focus on how and why interventions could be effective, and on the relationship between the interventions and local communities. The discussions do not substantively address the research and development costs of turning these ideas into operational tools, or the long-term costs of operating the interventions.

Initially, governments, perhaps with private-sector partners, should fund a research and development program to test and refine interventions. Such research and development will need to propose models for covering the actual cost of deploying and operating interventions, particularly in the early stages.

Longer term, carbon credits could perhaps cover operating costs for preventing permafrost thaw and/or reducing permafrost greenhouse gas emissions.

Last, it is important to remember that these interventions, although they would reduce total global greenhouse gas emissions, are essentially partial measures: if we can't stop or reverse the release of heat-trapping gases from the burning of fossil fuels, most of these interventions will eventually fail. Such interventions will only help slow the rising concentration of carbon in the atmosphere if accompanied by a rapid reduction in emissions and a ramp up of negative emissions technologies.

3.1 Criteria for assessing interventions

The UArctic compendium assesses each intervention against 12 criteria, including the intervention's technology readiness, scalability, and timeliness; the suitability of the intervention in existing governance structures; and the potential impact on local and Indigenous communities. Assessed values are presented on a three-point scale, typically (but not always) high, medium, or low (with defined criteria), as determined in UArctic-led workshops and discussions.

In some cases, the value is assessed as unknown, reflecting insufficient information to make a reasoned determination.

In this report, we focus on the three UArctic attributes we deem most relevant for understanding the viability and potential effectiveness of an intervention: its technological readiness, its potential scalability, and its timeliness—in other words: will it be available in time to make a difference? The UArctic compendium has formal definitions for these three criteria, which we summarize below.

The first three criteria assess the readiness of the proposed interventions—that is, how close they are to being ready to deploy to slow thaw or emissions. Only three of the proposed interventions are close to ready, and all 13 will need substantial investment to determine their effectiveness and to understand where they could be best applied.

The fourth criterion, *termination shock risk*, seeks to quantify the risk of suddenly discontinuing the intervention at some point in the future. This criterion is important for determining the magnitude of the commitment the intervention requires, as a rating of *high* likelihood implies a multi-generational commitment to sustaining the intervention, owing to the high likelihood of massive climate disruption should it be suddenly stopped.

The compendium also assesses, for each intervention, the likelihood of environmental risks, the risk of negative (or positive) impacts on local and Indigenous communities, and the ease of reversibility of the intervention (how easily it can be turned off). Often, the assessed values are "unknown," reflecting our limited understanding of the intervention. These will be important criteria to continually assess as our understanding of the interventions improves.

Criteria colour-coding

We colour-code the ratings to provide a visual shortcut for gauging interventions: green means safety, yellow means caution, and red means danger (or unknown). We have also, in some cases, shortened the criteria names from those found in the compendium, to make it easier to include the names in summary tables. We provide both names in the following criterion descriptions.

1. **Technological readiness** (labelled **technological readiness level** in the UArctic compendium) characterizes the maturity of the science behind the potential intervention, leveraging the Horizon Europe *technological readiness level* scale (*TRL Scale in Horizon Europe and ERC, Explained*, n.d.). The scale ranges from one through nine, with definitions in the following table. For simplicity, the UArctic team grouped these into three readiness categories: low, medium, and high. We have again added the red-yellow-green colour scheme, which we use in summary charts and tables.

Rating	TRL scale—technological readiness level	
 **LOW**	1: Basic principles observed. 2: Technology concept formulated. 3: Experimental proof of concept.	Technology is far from ready, and will likely take many years before its effectiveness is known.
 **MED**	4: Technology validated in lab. 5: Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies). 6: Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).	Technology has proven effective in appropriate test environments, but is not operationally proven.
 **HIGH**	7: System prototype demonstration in operational environment. 8: System complete and qualified. 9: Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies, or in space).	Technology has proven effective in an operational environment.

Even with moonshot-level investment and R&D, technologies rated *low* can be expected to take many years to develop, test, and pilot before being ready for deployment.

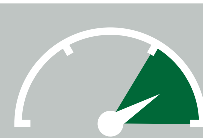
2. **Scalability:** Assesses how well or easily the intervention could be replicated to cover wider or different geographical areas, including the efficiency of this scalability.

LOW

Physically unable to scale, sub-linear or logarithmic efficiency of scalability. There are essentially no economies of scale.

MED

Somewhat able to scale, linear efficiency. Effort would likely scale linearly with increasing coverage.



HIGH

High ability to scale; exponential efficiencies. Could likely scale up to cover much larger regions for only an incremental increase in costs.

3. **Timeliness:** (labelled **timeliness for near-future effects** in the compendium) assesses the likelihood that we can get the solution in place in sufficient time to make a significant difference in the next 20 years.

LOW

Likely can't be implemented in time to make a significant difference.

MED

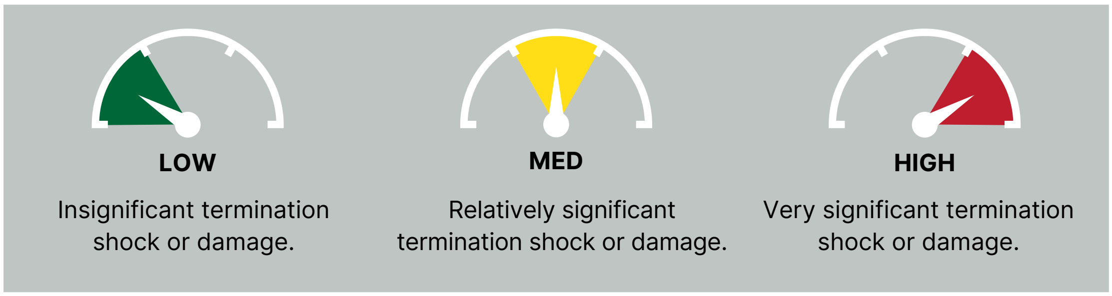
May be implementable in time to make some difference.

HIGH

Implementable in time to make a significant difference.

Timeliness is *high* when the activity needed to deliver the intervention is already used and well-understood in a different context. For example, wildfire suppression is a well-established forest management practice that could be leveraged as a permafrost protection intervention to minimize permafrost thaw. We also know how to inject aerosols into the stratosphere, which is a key requirement for several atmospheric interventions—but we don't yet understand how to ensure the desired climate impact.

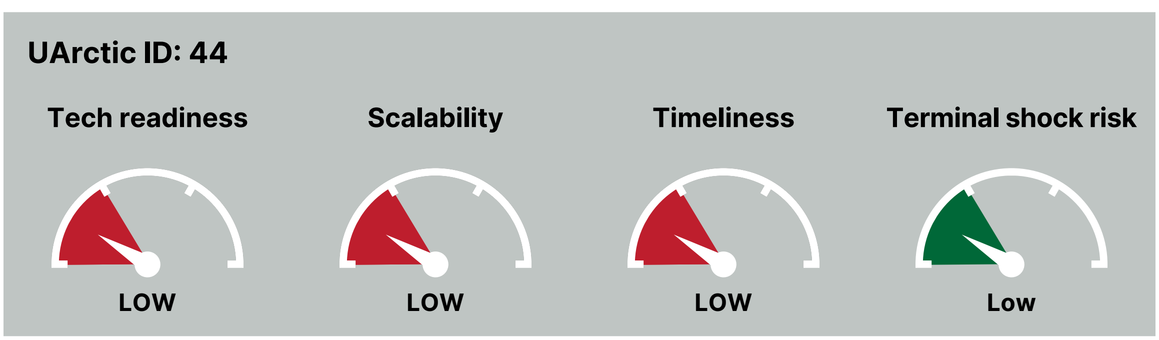
4. **Termination shock risk** (labelled **likelihood of termination shock** in the compendium) assesses the risk of a serious environmental impact if the intervention is suddenly ended. Note that in this case, *high* means high risk (and is thus colour-coded as red) while *low* means low risk and is coded as green.



For many interventions, there is essentially no climate impact from stopping use of the intervention, so the termination shock risk is low. But termination shock risk is high for solar radiation-blocking interventions such as space-based solar radiation management, which proposes cooling the Earth by blocking portions of solar radiation. Suddenly stopping such an intervention would cause temperatures to spike, leading to a large climate shock, and therefore a high termination shock risk.

Assessment dashboard

Assessments for each intervention are summarized at the start of each intervention description using the following format. The UArctic ID is the numerical reference used in the published UArctic Survey of Interventions (van Wijngaarden et al., 2024).



3.2 Summary of interventions

This section provides an overview of the portfolio of thirteen proposed interventions, summarized in Table 1.

TABLE 1:
Overview of the assessed interventions

UArctic ID	Intervention	Tech readiness	Scalability	Timeliness	Termination shock risk
1. Interventions with local impact					
44	Enhanced permafrost freezing with air pipes				
-	Snow compaction in winter			?	
-	Draining of thermokarst lakes/regions	?	?	?	
41	Conservation and restoration of peatlands and wetlands in taiga and tundra				
2. Interventions with regional impact					
37	Wildfire management				
39	Caribou herding				
40	Rewilding of permafrost regions				
-	Engineered methanotrophs		?	?	?
49	Methane flaring (not industrial)			?	
3. Interventions with global impact					
20	Arctic winter stratospheric aerosol injection				
21	Cirrus cloud thinning		?	?	
22	Mixed-phase regime cloud thinning		?	?	?
24	Space-based solar radiation management				

Summary of assessments for the 13 potential interventions discussed in the paper.

The information in this table allows for useful observations about the overall portfolio and about potential strategies for moving ahead, which we discuss below. The following section discusses each of these interventions in more detail.

1. There are three ready-to-go interventions

Three interventions—conservation or restoration of peatlands and wetlands, wildfire management, and caribou herding—are essentially ready to be piloted as interventions to protect underlying permafrost, mainly because they would simply be variants of existing land management practices.

2. The other 10 interventions are far from ready

Most of the interventions are red (low or unknown) across technological readiness, scalability, and timeliness. Red technological readiness means the approach is likely many years from being ready for real-world testing and deployment. This generally reflects three challenges: the lack of R&D funding to develop, test, and prove the intervention; the lack of public support for needed real-world testing and validation; and the long timelines (multiple years) such experiments would need to run.

3. All global impact interventions likely have high termination shock risk

High termination shock risk means that, should the intervention be suddenly shut down, the impacted region would experience sudden and dramatic increases in temperature, causing a major climate shock. Moreover, if the impacted region is large enough, the climate shock would likely be global.

Consequently, global impact interventions with high termination shock risk would need to be operated and governed on a global scale, to account for this global risk and to ensure there are sufficient financial and other resources available to sustain the interventions for decades or centuries.

4. Initial thoughts on a plan

Given the current state of the research, a thaw mitigation program should likely start with the three interventions deemed ready to deploy. They can be used to learn how to run, monitor, manage, and optimize an interventions portfolio to achieve emissions reduction targets, and to develop a successful, community-integrated operating model.

In parallel, there will be a need for a research and development program to explore the less-developed interventions and transform them into proven, practical tools. Once proven, these tools could be onboarded into the thaw mitigation program.

There will likely be synergies and overlaps between these two activities, and this should be reflected in how the programs operate.

3.3 Interventions with local impact

Interventions in this category are *local* in that they are known to control thaw in small areas but could scale up geographically. Local-impact interventions typically work by physically modifying or adding infrastructure to the landscape to encourage heat flow from the ground into the atmosphere, to slow the decay of organic material, or both. Many of these are scaled-up versions of interventions originally developed to stabilize permafrost below built infrastructure such as buildings, industrial facilities, urban settings, or roads.

These interventions are also local in that their impact is geographically constrained to where the intervention is applied: they cannot expand beyond that location without human effort to replicate the intervention elsewhere.

Local interventions involve an initial installation expense as well as ongoing operational expenses, which are both directly related to the size of the area where the intervention is implemented. As a result, the overall cost grows rapidly as the intervention is scaled up—there are few economies of scale. Decommissioning the intervention and removing installed infrastructure if or when it is no longer needed would also likely prove costly.

As a result, the scalability of most local interventions is rated *low*.

Local-impact interventions are likely to entail significant secondary environmental impacts when applied at scale in pristine landscapes, due to the need for access routes to install and maintain supporting infrastructure, as well as potential interactions between the infrastructure and the ecosystem.

However, termination shock risk is believed to be low for local interventions, since terminating the interventions will not lead to a sudden change in temperature or climate.

Enhancing permafrost refreezing with air pipes

Technologies already exist for active cooling of small regions of permafrost at risk of thawing. Thermosyphons—a passive cooling technology requiring no external power source—have been used in the Arctic since the early 1970s to cool and stabilize permafrost below built structures such as buildings or industrial facilities (arcticfoundations, n.d.-b; Holubec, 2008). For example, the Trans-Alaska pipeline, constructed in the 1970s, uses roughly 120,000 thermosyphons to stabilize the 1,280-kilometre-long pipeline and related infrastructure such as pumping stations by preventing permafrost thaw (Wagner, 2014). Similarly, northern industrial facilities such as tailing ponds can be stabilized by freezing the soil, for example using powered refrigeration systems and buried cooling pipes.

In principle, one could extend this measure to cool permafrost more broadly. For example, one could place a network of thermosyphons in wilderness permafrost regions, or insert horizontal pipes into the permafrost layer to extend the cooling range, or add powered refrigeration systems to pump chilled, sub-zero refrigerant through buried pipes (arcticfoundations, n.d.-a).

So far, such infrastructure has only been used to cool industrial facilities (mines, pipelines, waste storage facilities, buildings) where the physical area to be cooled is small, infrastructure to access and power the intervention is nearby, and the direct benefits of the intervention outweigh the costs.

There has been little research on the effectiveness, risks, benefits, costs, and scalability of using ground-cooling technologies to enhance or stabilize large regions of permafrost at risk of thaw, which explains the UArctic's *low* rating for technological readiness and scalability. Also, installation, maintenance, and eventual decommissioning across large areas of permafrost would be expensive and environmentally disruptive.

Snow compaction in winter

UArctic ID: n/a

Tech readiness	Scalability	Timeliness	Terminal shock risk
LOW	LOW	UNKNOWN	LOW

Freshly fallen snow is an effective insulator, keeping the ground beneath the snow warmer than the atmosphere above (Morse et al., 2012). Compacting snow improves its thermal conductivity, improving cooling of the ground and reducing the warming impact of thicker snowfalls.

This has been validated in small-scale field experiments (Jardine et al., 2024) using snowmobiles to pack down snow adjacent to roadways, and then monitoring ground temperatures over time within and around the compacted region. Results showed compaction led to lower ground temperatures compared with unpacked snow regions, both in and somewhat beyond the compacted region.

In principle, this intervention could be scaled up to larger regions, given sufficient personnel and equipment, a suitable landscape (easy access by snowmobiles or by some other compaction technology), and snowfall amounts sufficient to make the compaction impactful.

Questions remain, however, regarding the long-term impact on the ecosystem of repeated interaction with snowmobiles or other compaction equipment (noise, environmental disturbance, damage to groundcover, long-term compaction of active layer soil). This intervention is thus likely to have a significant environmental impact. Full analysis will also need to account for carbon emissions from fuel burned by snowmobiles and other equipment: it is possible the climate change benefit of compaction may not outweigh the climate cost of executing the intervention, if it is done with fossil-fuel-burning equipment.

The scalability of this intervention in areas distant from human settlements, highways, or well-travelled snowmobile routes is also in doubt. As with other interventions in this category, there are no obvious economies of scale for treating larger geographies. It is also unclear if this intervention could be applied quickly enough to meaningfully slow permafrost thaw, so we rate the timeliness of the intervention as *unknown*.

Draining thermokarst lakes

UArctic ID: n/a

Tech readiness	Scalability	Timeliness	Terminal shock risk
UNKNOWN	UNKNOWN	UNKNOWN	LOW

Water plays a key role in the formation and dynamics of thermokarst regions and lakes, with water flow triggering accelerated, often non-linear thaw and leading to a rapid rise in greenhouse gas emissions.

However, natural drainage of thermokarst lakes can slow this activity, leading both to slower thaw and to reduced greenhouse gas emissions (Göckede et al., 2019; van Huissteden et al., 2011). In addition, natural drainage of thermokarst lakes and regions is known to lead to increased plant growth, which can increase the rate of carbon sequestration (Chen et al., 2023; Loiko et al., 2020).

Drainage can also reduce the production of methane, which primarily happens in the anoxic (oxygen-free) environments found in still lakes or in water-saturated soil. However, water drained from such regions will be laden with suspended organic material, which can subsequently decay, releasing either carbon dioxide or methane should the organic material again find itself in an anoxic environment. Work is needed to understand if and under what conditions the net emissions savings from drainage outweigh the emissions released by the drained water.

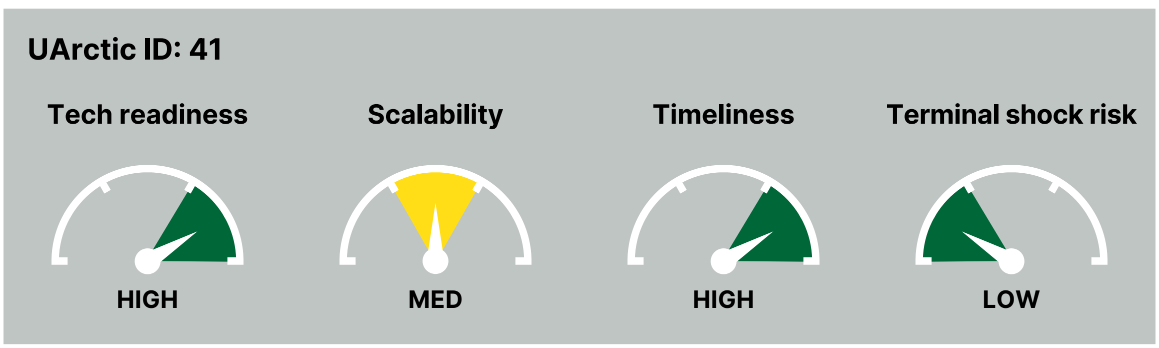
Indeed, there is also research arguing for preserving and better managing wetlands and peatlands, as opposed to draining, to both preserve the underlying permafrost and to maintain the carbon sequestration capabilities of the surface ecosystem. The next intervention, conservation and restoration of peatlands and wetlands in taiga and tundra, examines this opposite approach.

It is possible that both interventions are effective, but under different circumstances, or indeed that partial drainage of thermokarst lakes might in some cases be an even better approach. For example, conservation and preservation of wetlands and peatlands may be the best approach for certain terrains and up to a certain threshold of degradation, outside of which draining and more active management may be the better choice. Further research is needed to know if or when draining thermokarst lakes is an effective and appropriate approach for long-term reduction of greenhouse gas emissions.

We assess technological readiness for this intervention as *unknown*, since the capability to drain lakes or bogs is understood but the details of how and where to do this to achieve long-term emissions reductions are not. We also propose that scalability is unknown, as the cost of building and maintaining drainage infrastructure should scale well with increased areas, but this has not been tested. We assess termination shock risk as low, as stopping the intervention is straightforward and should only have limited and local impact.

On the other hand, it is not known if this intervention may introduce environmental risks, or if it is reversible: it likely is not. It is also important to note that local and Indigenous populations can depend on wetlands and peatlands for water, fishing, and hunting, so the impacts of such a massive transformation of the ecosystem could be profound.

Conservation and restoration of peatlands and wetlands in taiga and tundra



Northern peatlands and wetlands, areas seasonally covered by water, play important roles in the global carbon cycle, releasing both carbon dioxide and methane (the latter due to anaerobic decay in the water and peat) and sequestering carbon as plants or trees grow, die, and are incorporated into the ground. Moreover, most Arctic peatlands and wetlands lie on top of permafrost, insulating the permafrost from surface heat and, until recently, contributing new material to the permafrost layer over time. Such terrain is often important to local communities, as a source of food (fish and other wildlife) and as an environment for raising and herding caribou.

These environments are being affected by climate change due to changes in temperature and weather as well as indirect factors such as increased risk and severity of fire. In addition, human activities such as land clearing or water drainage are damaging these ecosystems, impacting the land's ability to sequester carbon and protect the underlying permafrost.

For these reasons, the *Technical Summary* of the Working Group III (mitigation) contribution to the Sixth Assessment Report of the Intergovernmental Panel on

Climate Change (Pathak et al., 2023) recommends aggressive monitoring and restoration of wetlands and peatlands so as to improve their ability to sequester carbon and protect deep-lying permafrost, and to preserve these ecosystems. The *Resilience and Management of Arctic Wetlands* report from the Arctic Council Working Group (Conservation of Arctic Flora and Fauna, 2021) provides a template for potential beneficial interventions, most of which involve improved water management to sustain wetlands and peatlands.

Because intervention approaches are already understood, the technological readiness level is seen as *high*. The UArctic analysis assesses the scalability as *medium* owing to the high carbon mitigation potential of the intervention, but more work in Arctic regions will be needed to verify this, as the previous work estimating the mitigation potential did not focus on the North (Roe et al., 2021). The compendium also assesses timeliness as *high* because the capability already exists and can be deployed almost immediately.

Note that this intervention essentially means maintaining or adding water to wetlands or peatlands to preserve the existing ecology. This should be contrasted with the previous intervention, which recommended lake drainage. This contradiction highlights the fact that the specific state of different but often similar environments (wetlands versus thermokarst lakes) may lead to quite different emissions reduction interventions.

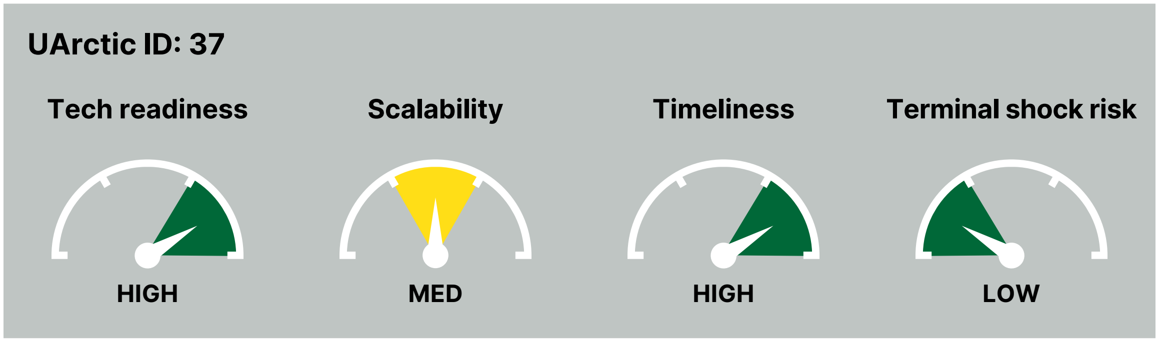
It is also important to note that natural, land-based interventions (wildfire management, restoration of wetlands and peatlands, caribou herding, and rewilding) can easily overlap in the same geographical area, either intentionally or accidentally, and will then interact with each other. Such overlaps need to be properly researched to understand if or how they can be managed together to deliver the desired outcomes.

3.4 Interventions with regional impact

The *regional impact* category consists primarily of land-use interventions that involve changing how humans manage ecosystems. These interventions need to be deployed over a wide surface area to be effective, but in most cases could be contained to the region in which they are deployed.

Because the goal would be to use these interventions over large regions, there is a high likelihood that different interventions will eventually overlap and interact, potentially to ill effect. There has been little work looking at such interactions.

Wildfire management



Fires are a natural feature in Northern forests and bushlands, leading to direct greenhouse gas emissions from combustion and, long-term, to emissions from permafrost thaw as a result of fire damage. Fire can also threaten Northern communities through direct damage or through damage to the local ecosystem on which communities depend.

Warming due to climate change is leading to an increase in the number and intensity of fires, thus increasing the rate of thaw (Madaj, 2025; Gibson et al., 2018; Lipovsky et al., 2005, pp. 175–194). At the same time, research suggests that permafrost thaw can itself intensify northern wildfires (Kim et al., 2024) due to the impact of thaw on surface ecosystems. Given the potential for these mechanisms to jointly accelerate carbon emissions, there have been recent calls for more aggressive firefighting in the North and for different strategies for managing Northern forests (Phillips et al., 2022; Tollefson, 2024b), to protect the forests and the underlying permafrost. Fire risks and fire impact on permafrost can be reduced in several ways. First, prescribed burns, tree planting, and other land management practices can reduce both the risk and severity of fires, while extreme fires can often be controlled through aggressive and early fire suppression. Although costly, these activities may turn out to be economically worthwhile, as recent research suggests the cost of avoiding carbon dioxide emissions through increased fire management can be less expensive than other carbon emissions reduction strategies (Phillips et al., 2022).

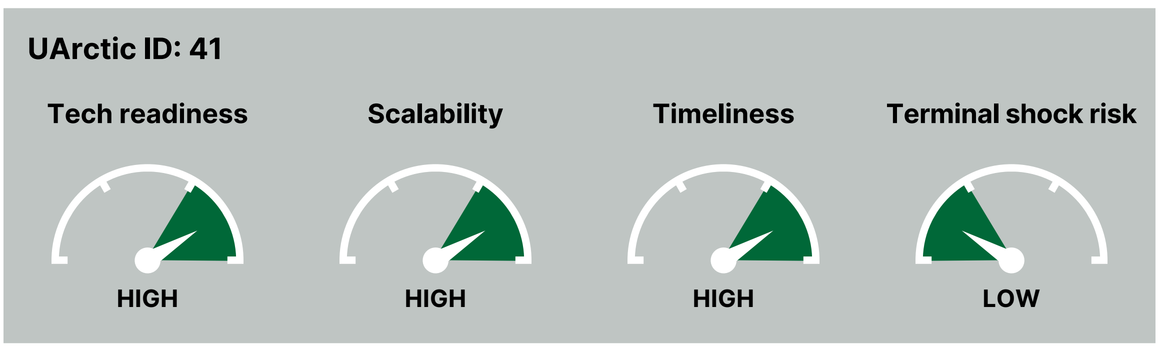
Second, it may be possible to reduce the likelihood of fires. Many fires (up to 55 percent in Northern forests) are caused by lightning strikes (Veraverbeke et al., 2017), with the number of such strikes having increased dramatically since 1976. If lightning strikes could be predicted and then prevented, this would reduce the overall number of fires. The startup Skyward Wildfire is developing tools for identifying and suppressing lightning strikes, with the aim of preventing wildfires (*Skyward Wildfire*, n.d.). Such work is in its early stages but, if successful, could significantly reduce Northern fires.

Fires will still happen, of course, so it will also be important, from a greenhouse gas emissions perspective, to have after-fire mitigation plans to help the surface ecosystem recover quickly and to restore forest or bushland, so as to protect the underlying active layer and permafrost.

By and large, firefighting has focused on protecting infrastructure and human lives and on preserving the economic value of forest resources. This focus does not factor in the permafrost and climate impacts of fire. This approach to fire-fighting must change if permafrost preservation and greenhouse gas emissions reductions are fire management priorities.

Wildfire management is one of the easiest interventions to implement, as the practices are well-understood and there is already a good understanding of the types of changes to make. Moreover, given humanity's long experience in fire management, there is a low likelihood of unanticipated environmental risks.

Caribou herding



As the only large northern herbivore, caribou[8] play an important role in northern ecology, through their grazing and subsequent defecation and from their physical impact on the ground.

These ecosystem interactions are believed to be helpful in preserving permafrost and sequestering carbon in the active layer. For example, in winter, shrubs tend to reduce airflow next to the ground, reducing ground cooling: thinning of shrubs by caribou increases airflow, and can improve winter cooling of the ground. Similarly, caribou compact snow by walking and sleeping on it, which improves conduction and helps cool the ground (Beer et al., 2020; Cartier, 2020).

Meanwhile, several analyses have found that global caribou populations have shrunk dramatically over recent decades (Osborne et al., 2018; Uboni et al., 2016; Vors & Boyce, 2009 National Oceanic & Atmospheric Administration, n.d.). This is

8 The UArctic Compendium refer to this intervention as reindeer herding rather than caribou herding, reflecting the more common European species name.

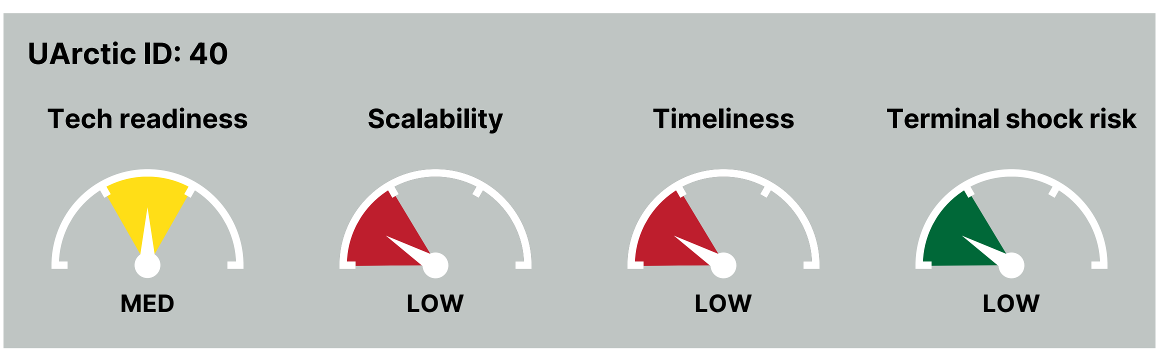
believed to be due to habitat change, likely caused by the warming climate, and to direct human causes including hunting, herding, and habitat destruction. Given reduced numbers and range, caribou populations are thus less effective at mitigating some of the impacts of the changing climate, just when such mitigation is needed most.

Recent research explores ways to leverage the benefits of caribou by protecting or expanding existing populations (for example, by reduced or managed hunting), or by herding them to locations with an elevated risk of permafrost thaw to maximize beneficial impact (Spiegel et al., 2023). Doing so will require changes in current land use and hunting practices, and the active support of local communities who will be coexisting on the landscape with a larger caribou population.

The technological readiness of this intervention is ranked *high* because caribou herding has long been practised by Indigenous Peoples, so new or different herding strategies can likely be introduced without difficulty. Scalability is also rated *high*, as it is believed that such strategies can be easily implemented and scaled up over the roughly 1.8 million square kilometres of traditional caribou territory worldwide. The UArctic compendium also suggests this intervention may have a beneficial impact on local and Indigenous communities, particularly those for whom caribou herding is of historical and cultural significance.

However, there may also be conflicts with existing husbandry or other land use practices, such as forest and wildfire management, or with land designed for industrial facilities such as mines or roads that may impede caribou migration. On the other hand, there may be synergies between caribou herding practices and other intervention recommendations, such as peatland restoration (Tarvainen et al., 2022). This is also an easily reversible intervention, as caribou could easily be removed from areas of concern.

Rewilding of permafrost regions



The rewilding concept argues that permafrost regions can be restored and re-invigorated by introducing, or re-introducing, large herbivores and predators, on the understanding that such animals have in the past impacted the ecosystem to improve active-layer soil carbon sequestration and to slow or stop permafrost thaw.

This idea is an extension of a broader movement that looks at rewilding as a strategy for restoring biodiversity and re-establishing self-regulating ecosystems across a range of global environments, while building a more holistic connection between people and nature (Torres et al., 2018).

One can also think of rewilding of permafrost regions as an extension of the caribou herding intervention, except that this version of rewilding intentionally introduces species not currently native to the ecosystem or region (for example, non-indigenous large herbivores, predators, and other species that could help transform forested areas into grasslands).

Environmentally, rewilding assumes permafrost preservation will be aided by restoring the ecosystem to a state like that which existed during the Pleistocene epoch (2.6 million to 11,000 years ago), and that reintroducing fauna similar to that era will help in this transition (Josh Donlan et al., 2006). Consequently, this is also sometimes called *Pleistocene rewilding*.

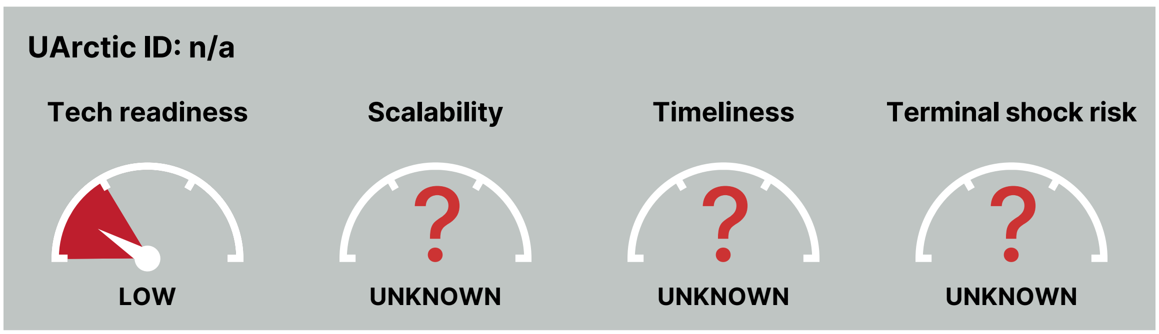
This idea is primarily being tested at Pleistocene Park, a 2,000-hectare field laboratory established in Russia's Sakha Republic in 1996 (Pleistocene Park, n.d.). Computer modelling work has suggested the approach could help preserve permafrost (Lucas & Enos, 2019), while experiments to date have shown beneficial environmental and permafrost-preserving effects from a wide variety of introduced herbivores, including bison, moose, musk ox, camels, and Yakutian horses (Fischer et al., 2022; Zimov, 2005).

One of the more provocative proposals has gone a step further, proposing the reintroduction of long-extinct mammoths (Stephanie Dutchen, 2021)—the elephant-sized megafauna of the Pleistocene epoch that went extinct roughly 4,000 years ago (Zimov, 2005). It is believed that, in that era, mammoths played a significant role in shaping Northern ecosystems. There is also evidence that human activity, including hunting, contributed to mammoth extinction (Carotenuto et al., 2018; Chatters et al., 2024). The proposal to re-introduce mammoths would involve "reversing" mammoth extinction by splicing bits of DNA recovered from frozen mammoths into the DNA of an Asian elephant.

Leaving aside technological and ethical concerns, there are many remaining challenges for the broader rewilding concept. First, pilot projects (such as Pleistocene Park) would need to be scaled up in size and diversity of species to reproduce the biodiversity of the late Pleistocene and to assess the impact on permafrost. Second, rewilding can only succeed with the active support of the local human, particularly Indigenous, population, as the introduction of new species could dramatically transform the ecosystem. Third, it is unclear how this model can be scaled up quickly and to a large enough scale to have a significant impact: the rapid warming of the Arctic may make it impossible to establish and sustain a Pleistocene-like environment in the Far North.

More positively, this approach could likely be implemented by, and limited to the geography of, a nation state (e.g. Russia's in their Northern taiga regions, or Canada, or the United States). It is also likely reversible, should pilot projects show insufficient climate benefits.

Engineered methanotrophs to reduce methane emissions



As noted earlier in this paper, methane has 30 times the climate-heating power of carbon dioxide, which is why there is growing concern about abrupt thaw events, which produce large quantities of this gas. Research, however, suggests that up to 60 percent of the methane produced during abrupt thaw processes is currently being digested by *methanotrophic bacteria* and converted into carbon dioxide before being released, substantially reducing the amount of methane reaching the atmosphere. If this conversion rate could be increased, for example by introducing into the permafrost engineered methanotrophs that could substantially raise the rate of conversion of methane to carbon dioxide, this could further reduce methane emissions and significantly reduce the climate change impact of abrupt permafrost thaw.

Independent of permafrost research, there has been considerable research on methanotrophic bacteria because of their ability to create commercial products from biological or other renewable source material in industrial bioreactors (Ahmadi & Lackner, 2024; Zhang & Rumah, 2024), as well as their ability to remove methane in industrial contexts (He et al., 2023). Recent research has also sought to better understand methanotrophic bacterial populations and their methane moderation potential in permafrost thaw environments (He et al., 2023; Keuschnig et al., 2022; Singleton et al., 2018). However, we have found no research aimed at identifying methanotrophs that would function well (better than naturally occurring bacterial species) in taliks or deep lake water, or that could improve the rate of conversion of methane into carbon dioxide and other compounds in these environments.

Nor have we found research on potential side effects of such engineered bacteria: we believe there is a real possibility of unanticipated impacts and environmental risks. These risks are all the greater given that this intervention would likely be irreversible since, once released, such bacteria could easily spread geographically and could likely never be eliminated from the environment.

Methane flaring (non-industrial)

Methane is a greenhouse gas with a global warming potential roughly 30 times greater than carbon dioxide over a 100-year timeline (United States Environmental Protection Agency, 2016). As noted earlier, methane can be produced by thawing permafrost thaw, but it is also produced naturally and continuously in small concentrations on land and in the oceans by a variety of natural processes.

Recent multi-year observational data have shown that methane emissions from monitored permafrost regions have been rising continuously since 2004 (Rößger et al., 2022). However, some studies also suggest that there may be natural limits to the quantity of such emissions (Heffernan et al., 2022), so uncertainty remains as to the long-term trend in permafrost region methane production and release.

That being said, there has been discussion on ways to mitigate this emissions risk, either by capturing the methane and putting it to use or by *flaring* it: burning it and converting it to less problematic carbon dioxide (Stolaroff et al., 2012). The main challenge lies in collecting and capturing the methane. In permafrost regions, methane is released in low concentrations across a wide area: it is hard to capture methane from dilute sources and process it to concentrations suitable for flaring.

If methane is concentrated in a specific location, such as an underground reservoir or a lake, it might be possible to capture it on site using existing methane capture technologies, but there is little evidence to date that methane from permafrost comes from such concentrated sources.

There has been some preliminary thinking on ways to gather and process diffuse releases of methane in Northern ice, ocean, or land (Lockley, 2012; Stolaroff et al., 2012), but little work to test practical approaches for methane collection and disposal above permafrost. Because of this, the technological readiness, scalability, and timeliness for this class of interventions is either low or unknown, as are the likelihood of environmental risks and ease of reversibility.

The termination shock risk of this intervention is believed to be low, as stopping the intervention should have a low risk of causing a shock.

3.5 Interventions with global impact

Interventions in this category operate on a continental or global scale by reducing solar energy arriving at the Earth's surface. For example, one intervention proposes space-based sunshades to filter out a portion of the light from the sun, cooling the shaded portions of the planet. Others look at atmospheric modifications (typically by injecting aerosols or other materials in the atmosphere, which are then distributed by wind patterns over a wide area) to either reflect sunlight away or to make clouds or the atmosphere more efficient at radiating heat into space, so that there is less energy available to be trapped in the atmosphere by greenhouse gases.

Such interventions are nearly impossible to constrain to a local region and, in some proposed implementations, can affect the entire planet. However, some interventions with global impact can, in principle, be somewhat localized. For example, if atmospheric interventions in the stratosphere happen far enough to the north (or south), weather and wind patterns will constrain the impact to the hemisphere in which the injection took place. Thus, such an intervention launched in northern Canada would impact northern North America, Greenland, northern Europe, and northern Russia. Certain cloud-seeding interventions can also be limited geographically due to the limited lifetime of seeding material spread in clouds.

Also, while it is generally assumed that space-based sunshade approaches would affect the entire planet's surface, proponents believe that shades could be designed to selectively impact portions of the Earth, such as the northernmost portions of the northern hemisphere.

Some global-impact interventions would have, quite literally, sky-high operating costs. For example, space-based interventions would require massive space-based infrastructure, which would require constant and expensive maintenance and support. Meanwhile, high-latitude stratospheric aerosol injection, which would require constant flights from a fleet of purpose-built aircraft or drones, is believed to be relatively cheap ($1 billion to $10 billion per year) compared with other climate mitigation strategies (National Academies of Sciences, Engineering, and Medicine, 2021).

If maintenance were to cease and the infrastructure failed, or if injections were to suddenly stop, the effect of the intervention would quickly disappear. The resulting snapback of temperatures as heat-trapping gases resume their work presents a high termination shock risk. For that reason, such interventions must be approached as extremely long-term endeavours, which would require international agreements and widespread cooperation to sustain.

Thus far, global-impact interventions have only been tested via computer models or small-scale laboratory or table-top experiments; none have been tested in the field. Some small-scale experiments have been proposed (for example, injecting small quantities of material high in the atmosphere and monitoring the impact), but none have been approved or conducted to date.

There is also an ongoing debate over whether we should even explore such interventions, given their high risks and uncertain consequences. At one extreme lies a proposal for an international non-use agreement (Biermann et al., 2022), which calls for a ban on funding, field experiments, patents, institutional support, and deployments for any work on such interventions. A more recent paper proposes a more balanced approach, and suggests that an outright ban on research would "deprive future policy-makers of knowledge and capability that would support informed decisions to safely and equitably limit climate risk" (Parson et al., 2024). The paper argues in favour of research on solar geoengineering options, balanced by a clarified governance framework and mechanisms for objectively assessing solar geoengineering risks and benefits.

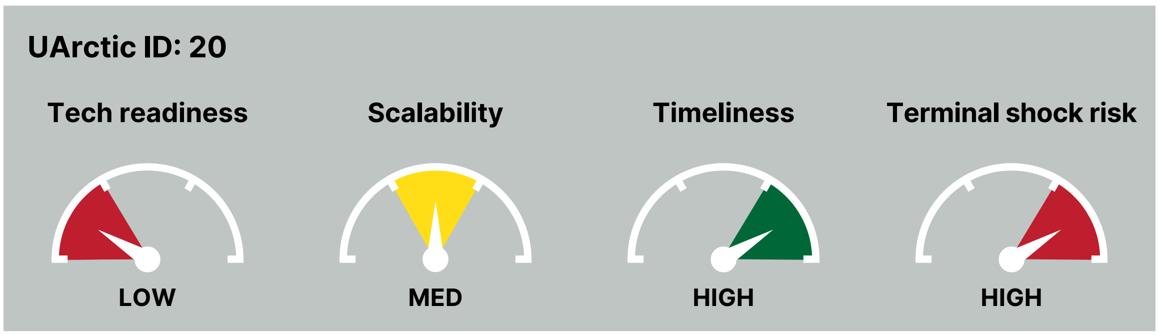
Insurance companies are also interested in this class of potential interventions (Swiss Re Institute, 2023), as they try to assess future impacts of the changing climate on insurance risk, and want to better understand how such interventions would impact their risk calculations.

Existing regulatory frameworks

Any atmospheric intervention would fall under the UN Convention on Long-Range Transboundary Air Pollution (United Nations, 1979), which obligates signatory countries to reduce emissions of certain air pollutants that can cross national boundaries. Similarly, the Vienna Convention for the Protection of the Ozone Layer (United Nations, 1985) obligates signatories to avoid activities that could degrade the ozone layer.

National and regional air, water, and ground pollution laws would also apply, given that atmospherically dispersed material will eventually precipitate onto the surface in snow or rain.

Arctic winter high-latitude seasonal stratospheric aerosol injection



This intervention counters heating by injecting aerosols such as sulphur dioxide into the stratosphere to reflect solar radiation, thereby reducing net incoming solar energy flux. This idea is modelled after, and in a sense validated by, the impact of large volcanic eruptions, which are known to cause substantial global cooling (often called “volcanic winter”) after large quantities of aerosols, dust, and chemicals are projected into the upper stratosphere.

The underlying mechanisms have been passively studied during and after volcanic events, by measuring cloud density and composition, solar flux, and aerosol concentrations and composition, combined with computer modelling of the atmosphere and the movement of energy through it. The focus of such research has been mainly on better understanding the effect of natural and anthropogenic stratospheric aerosols and dust on energy transport in clouds and the atmosphere, with an eye to developing more realistic climate models. Secondarily, this research seeks to better understand how volcanic eruptions temporarily influence the climate.

A practical implementation of this intervention would require a fleet of tanker aircraft able to transport large quantities of sulphur dioxide into the stratosphere and then disperse it across a target geography. Since near the poles the stratosphere starts at a lower altitude than at the equator, it is possible that existing aircraft (for example, a KC-135 tanker or modified commercial aircraft) could achieve sufficient, but not ideal, altitudes to serve this purpose. However, it is believed that such lower-altitude injections would require much larger quantities of aerosols than higher altitude injections, resulting in larger ground pollution impacts (Duffey et al., 2025). Thus, custom transports purpose-built to fly at higher altitudes may be the better choice.

Notably, there are no obvious technical obstacles to building higher-altitude transports: aircraft like the U-2 spy plane have flown to heights upwards of 20 kilometres since the 1950s. There has, to date, simply been no commercial motivation to build transport aircraft that operate at these altitudes.

Of course, focusing on transport is perhaps putting the cart before the horse. To date, there has been no experimental testing of this intervention, nor research to validate an engineered approach to stratospheric injections. In 2021, a group at Harvard proposed a set of small-scale experiments to test the basic ideas (Golja et al., 2021). But the proposal was withdrawn in early 2024 (Tollefson, 2024a) due to pushback by populations living in the regions where the experiments would occur, and due to social unease over the idea of engineering such large-scale changes.

It is also unclear what types of aerosols to use, whether the impacts can be limited regionally depending on where injections take place, or what the long-term impacts might be (for example, in water or ground pollution, as injected material or as by-products eventually precipitated out of the atmosphere).

It is believed that injected high-altitude aerosols can be constrained to the Arctic (or similarly to the Antarctic) as stratospheric airflow should move injected particles polewards and keep them there until they precipitate out.

The compendium assessment rates the technological readiness of this intervention as low, as study of the idea to date is limited to computer models. However, once proven, the concept should be straightforward to implement and scale up, likely within a decade, leading to a timeliness rating of *high*. Scalability is ranked *medium,* as dispersing aerosols at high latitudes should allow for cooling over a large portion of the Arctic, but not for more precise targeting.

This intervention is easy to reverse (just stop injecting aerosols), but has a high termination shock risk, since temperatures would subsequently rise dramatically. The intervention also introduces its own potential environmental risks, due to both precipitation of the injected aerosol material onto the ground and to the environmental impact of potential changes in cloud cover, precipitation, and light levels.

Cirrus cloud thinning

High-altitude (4,000-20,000 metre) cirrus clouds, composed mainly of small ice crystals, influence the Earth's radiation budget by reflecting radiation, both incoming (from the sun) and outgoing (longer wavelengths from the ground). But clouds are understood to be more effective at reflecting longwave radiation back towards the surface, leading to net warming.

Computer models suggest that thinning these clouds could reduce their ability to trap longwave radiation. This could be accomplished by seeding the clouds to stimulate water crystal nucleation, which would reduce both the cloud reflectivity and their lifetime (Storelvmo et al., 2013). Functionally, the process would be similar to injecting stratospheric aerosols, but would involve seeding different clouds with different materials such as sea salt or bismuth triiodide (Lawrence et al., 2018).

Some computer modelling suggests cloud seeding would be particularly effective at high latitudes, owing to existing low background concentrations of aerosols compared with clouds at lower latitudes (Lawrence et al., 2018; Storelvmo & Herger, 2014). However, other models suggest that seeding would only yield small changes in reflectivity and warming (Penner et al., 2015). It is also not clear how this intervention might impact other climate attributes, such as regional temperature distributions or patterns of precipitation, nor is it known how localized or dispersed such impacts might be.

This idea has a technology readiness rating of *low,* as there is no experimental (laboratory or in-the-field) work to confirm it would be effective. As with aerosol injection, most studies assume it would require fleets of dedicated piloted aircraft or drones to deliver and disperse seeding material. This approach means the intervention should scale well and be quickly deployable, leading to a high timeliness rating.

While this intervention is easy to reverse—simply stop seeding—and it could be reversed slowly, it has a high risk of termination shock. Cloud seeding could also cause secondary environmental impacts (due to precipitation of the seeding material in rainfall), but there has been no research to estimate the potential severity of such impacts.

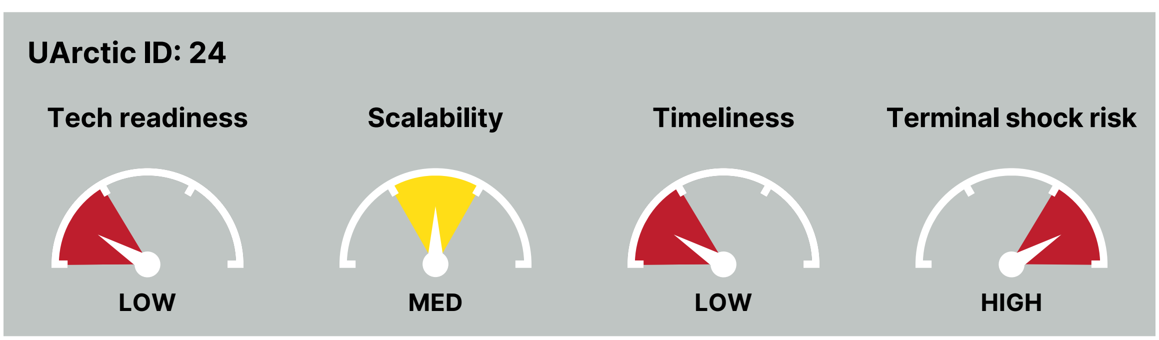
Mixed-phase regime cloud thinning over the polar oceans during winter

Mixed-phase clouds are found at relatively low altitudes (2,000-10,000 metres) and contain water in three phases: water vapour, ice particles, and supercooled water droplets. Although such clouds are poorly understood (Hofer et al., 2024), research suggests they could be thinned by cloud seeding, as with cirrus cloud thinning, and that such seeding would reduce the cloud's ability to trap heat close to the ground (Villanueva et al., 2022).

There has been limited research on these clouds, which is reflected in the brevity of this description and in the UArctic review and ratings. As with other cloud seeding options, this intervention could likely be limited to relatively small geographic regions.

The termination shock risks, ease of reversibility, likelihood of environmental risks, and impact on local/Indigenous communities for this intervention were all rated as *unknown*, as this intervention is not well-enough understood to hazard a rating.

Space-based solar radiation management



This intervention calls for placing infrastructure in outer space between the Earth and the sun to reflect a portion of incoming solar radiation, reducing the amount of energy reaching the atmosphere and thereby cooling the planet.

In most proposals, this intervention involves placing infrastructure (sunshades or reflectors) at the L1 Lagrange Point (NASA, 2018), which lies on the line connecting the Earth and the sun, 1.5 million kilometres inside the Earth's orbit. Objects positioned at L1 would stay at that location, constrained by the balance of gravitational forces between the Earth and the sun.

Infrastructure placed there would be designed to deflect or filter radiation heading from the sun towards Earth, reducing the amount of incident solar energy: less solar radiation means less heating. This does not fix the planet's global warming problem but compensates for it—analogous to putting a giant parasol on top of a greenhouse to block out some of the arriving light.

In most proposals, the infrastructure at the L1 point would be controllable, such that we could control the amount of sunlight incident on different regions of the Earth. This, for example, might let us cool polar regions more aggressively than central latitudes. However, this also presents new climate risks, as the Earth's weather systems would have to rebalance—in unpredictable and potentially destructive ways—in response to the changed distribution of energy arriving from the sun.

There have been several proposals for solar radiation management infrastructure at the L1 Lagrange Point (Baum et al., 2022), but none has progressed beyond the conceptual stage. Given the cost and complexity of this intervention, the compendium assesses both its technological readiness and timeliness as *low*. Scalability, however, is expected to be *medium*, since infrastructure, once in place, could make it possible to cost-effectively affect large portions of the Earth.

Termination shock risk is high, since the whole planet would heat quickly if the intervention were suddenly terminated, leading to unpredictable and potentially catastrophic shifts in weather and climate.

It would be decades before we could implement such infrastructure, at an estimated cost of US$20 trillion (Baum et al., 2022) or more. In the short to medium term, it is thus unrealistic to expect space-based interventions to be useful for managing permafrost thaw.

4. Conclusion: A plan for mitigating permafrost thaw

With complex thaw and emissions problems to solve and roughly five million square kilometres of the North underlain by permafrost, Canada needs a national program to tackle permafrost thaw. This program would require long-term support and engagement from the federal government, relevant provincial and territorial governments, and from key Northern stakeholders and community leaders.

Such a program to reduce thaw and preserve Northern ecosystems will need to address five linked challenges:

- **Better understanding of the science of thaw and associated emissions.** To slow or stop thaw, we need to better understand and predict how, where, and why thaw and the resulting emissions are happening.
- **Better data about permafrost regions.** Researchers need more and better long-term data to support addressing all questions related to thaw, emissions, and their mitigation.
- **High-quality permafrost forecasting models.** We need numerical models of the North that can let us know where, when, and how thaw and consequent emissions will take place, and that can identify where (and which) interventions may be appropriate.
- **Thaw and emissions mitigation toolkits.** Researchers need to develop and prove practices that can slow or stop thaw, and reduce or stop carbon emissions—work that will take time and that will demand substantial resources and deep community support.
- **An operating model for governance and decision making.** All thaw mitigation work must be framed under a governance model that engages and has the support of all stakeholders (including local communities). This would include engaging with the public to explain the nature, scope, and results of this activity.

Funding will initially need to be provided by governments (federal, provincial, territorial, municipal), potentially including private-sector and academic partners. Governance and oversight will need to involve governments and impacted local communities.

Over the longer term, when such a program has delivered key components of this mandate, Canada will likely need a dedicated organization—with its own mandate and operating model—to operate and manage a long-term thaw and emissions mitigation program. At a high level, such an organization could be mandated to:

- Plan, deploy, monitor, and manage a program of thaw interventions, including ongoing monitoring of the intervention program's environmental and emissions impacts.
- Provide ongoing reporting and public outreach to communicate the work and its results.
- Create a governance model to draw leadership from local, regional, Canadian, and global stakeholders.
- Secure sustained funding, perhaps through carbon credits for successfully preserving carbon in permafrost.

Every other permafrost country (Russia, China, Mongolia, the United States, Greenland, and the Nordic countries) will soon be facing the same thaw management challenges, making them natural partners in such a program. Moreover, current permafrost research is already looking closely at the impact of global warming on the permafrost environment, so we see this recommendation as an evolutionary but necessary step.

A cautious approach would suggest deferring the establishment of a program to address permafrost thaw until technical and scientific understanding of the mechanisms driving and accelerating thaw improves. But given the accelerating rate of climate change, and the likelihood that thaw mitigation experiments will need to run for years to deliver useful results, it is critical to start this work as soon as possible and learn as we go.

Coordinating work across all these areas will require collecting and analyzing massive amounts of time- and geography-dependent data on the weather, climate, greenhouse gas emissions, surface ecosystem and landscape, and subsurface properties across permafrost regions. Indeed, big data will be key to researching and understanding the current state of the environment, to forecasting the future state, and to monitoring emissions reduction projects.

This type of work calls for a centralized, supported, and dedicated permafrost data repository covering the Canadian landscape and beyond, where researchers can store, analyze, and share data, build and test models, and collaborate —something permafrost researchers are already calling for (Gruber et al., 2023). Such a repository and the supporting infrastructure would facilitate several valuable capabilities, such as:

- sharing of data,
- collaboration among researchers and research groups,
- shareable tools and models for forecasting warming-driven changes in permafrost,
- creation of permafrost thaw risk maps,
- tools for assessing the impact of interventions, and
- standardized reporting on the state of the Arctic.

Indeed, such a platform would both preserve key information and provide valuable infrastructure that could grow and evolve to support permafrost researchers as well as an active permafrost thaw and emissions mitigation program.

Indeed, the creation of this resource—with an appropriate ownership and governance model to ensure collaboration and information sharing—could be an ideal first technical step towards a permafrost thaw mitigation program.

CASE STUDY:

A Canadian plan for flood management

Although flooding is a simpler problem, Canada has a program underway to address the rising threat it represents—another consequence of our changing climate.

In 2015, the Canadian government began work on a National Disaster Mitigation Program, which included work on mitigating the risk and cost of recurring flooding (Natural Resources Canada, 2022).

This led to a Canadian government investment in 2023 of over $227 million, as part of Canada's climate National Adaptation Strategy, in a Flood Hazard Identification and Mapping Program (Natural Resources Canada, 2023), which will run through 2028 and create a national database and platform to support flood risk mapping to aid in planning flood risk mitigation projects (Snape, 2024).

Engaging municipal, provincial, private-sector, and other stakeholders from across the country, this program is creating a Canada-wide flooding model and GIS database, giving regions a common platform for loading data (geographical, weather, climate) and for running simulations to assess flooding risks. This multi-year program will improve the ability of communities, regional governments, and other stakeholders to forecast and plan for flooding, and to identify locations for flood mitigation projects.

Recommendations

In Canada, addressing the permafrost thaw threat will require long-term support from government, as well as ongoing input and leadership from impacted communities and peoples.

Indeed, a successful Canadian program will need strong and sustained pan-Canadian support. Of course, permafrost thaw is a global challenge, and such a program will need to collaborate with other, similar programs around the world. But such work can only be sustained if it is clearly supporting and providing value to Canadians.

Faced with this national challenge, the Canadian federal government should take the lead in creating a permafrost thaw mitigation program, starting with bringing together Canadian political and community leaders, permafrost science experts, and other stakeholders to develop a mandate. Such a task force could be chartered to come up with:

- a clear and compelling problem statement;
- identification of potential risks, opportunities, strengths, and gaps;
- a program governance model, including stakeholder engagement;
- high-level goals, success metrics, and potential intermediate milestones; and
- an initial program budget, structure, and operating model.

Given the nature of the challenge, such a program will require substantial resources, will need to run over many decades, and will need to be adaptable to changing circumstances and realities. It will thus be critical to create a flexible and resilient operating model.

Canada has more permafrost than any country but Russia and has the deep science-and-technology foundation and industrial base needed to tackle these problems. And with strong working relationships with other Arctic nations, Canada is well-positioned to play a leadership role in a global effort to tackle this problem, for the benefit of all.

Appendix 1:

Arctic amplification and a permafrost thaw tipping point

The status of our changing climate is often summarized in a single number, the global average surface temperature—a temperature averaged both across the planet's surface and over a full year of measurement. Year-over-year trends in this temperature, compared with a baseline, tell us how swiftly the climate is changing. By convention, the baseline or starting point is taken as the global annual average temperature averaged over the period 1850-1900. Compared with this baseline, measurements show that, as of today, the Earth's global average temperature had risen by approximately 1.54 ± 0.06 °C in 2023, with most of that rise happening in the past 40 years (World Meteorological Association, 2024, 2025a).

But climate change impacts different parts of the world differently, and the global *average* temperature doesn't reflect how temperatures change regionally. Arctic regions are warming far more quickly. A recent analysis of data gathered since 1979 has shown that, in the Arctic, average temperatures are rising roughly four times faster than the global average (Rantanen et al., 2022), with a synthesis of satellite observations already highlighting the impacts of this temperature rise (Esau et al., 2023).

This phenomenon, known as Arctic amplification, is believed to be due to several factors, including the loss of northern sea ice, changing cloud cover, and atmospheric changes that are affecting how solar energy is transferred through the atmosphere (Boeke et al., 2021). Whatever the cause or causes, this amplification is expected to persist as the planet continues to warm, amplifying the threat of permafrost thaw. And as thawing permafrost releases more and more carbon into the atmosphere, there is increasing risk of a permafrost thaw *positive feedback loop*, wherein the warming environment, which is already causing permafrost thaw, triggers the release of more carbon dioxide and methane, which in turn further accelerates warming and adds to this amplification effect—and on and on. Such a feedback loop could lead to much more rapid, unstoppable thaw, with a calamitous impact on the global climate.

To be clear, there is no evidence today that such a positive feedback loop has yet taken hold, and carbon emissions from permafrost are still a small fraction of those from other sources. So, for now, the risk seems low.

But science still has only a limited understanding of the Arctic amplification mechanism, and of how quickly permafrost thaw processes can be accelerated by faster-rising surface temperatures. Indeed, climate models have limited ability to forecast local climate variability, such as those due to Arctic amplification (Chylek et al., 2022), so forecasting long-term implications of such phenomena is extremely difficult.

It is safest to think of runaway permafrost thaw as a potential *pernicious tipping point* lying at some point in the future—but one that, if it occurs, is likely unstoppable once triggered, with catastrophic consequences for Earth's climate.

Appendix 2:

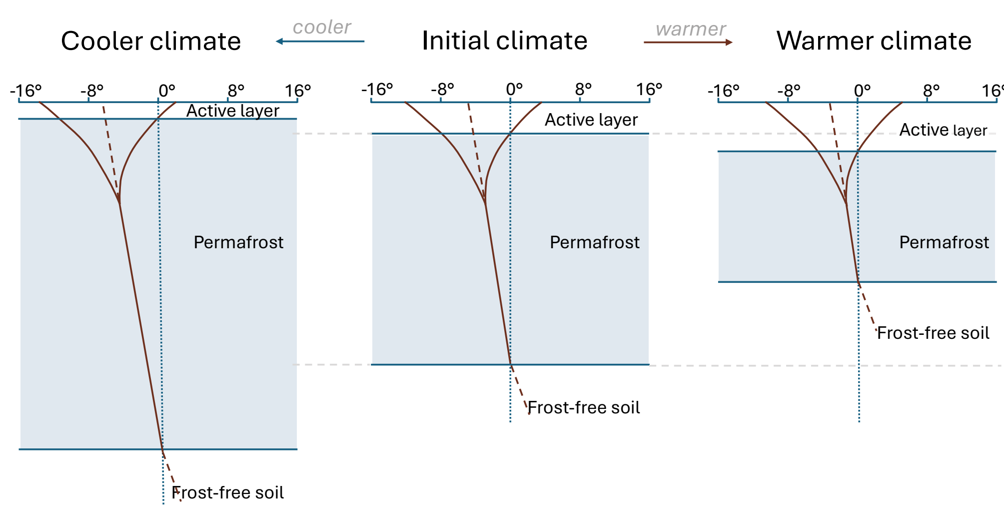
Permafrost thaw, formation, and emissions

As noted in the paper, the vertical temperature profile of permafrost regions—warmer at the bottom and cooling towards the top—is a consequence of heat flowing up from the warmer Earth below, through the permafrost and active layers, and out into the cooler environment above. When the climate is stable, this system is in equilibrium, and the layers of material (active layer, permafrost, soil below the permafrost) stay largely unchanged,[9] with the layered structure shown in Figure 2 (Section 2.1).

We can also leverage the model described in Figure 2 to qualitatively understand the impact of a cooler or warmer climate. Figure 5 takes the steady-state equilibrium profile of permafrost (centre), and contrasts this with equivalent steady state profiles under a cooler (left) or warmer (right) climate. In all three, the thermal or heat-conducting properties are considered the same (in other words, the lines have the same slope). The only difference lies in the change in the average temperature at the surface.

FIGURE 5:

The active layer thickens and permafrost thins as the climate warms



A simplified model of the vertical temperature profile through permafrost showing the effect of a cooler (left) or warmer (right) surface climate on the permafrost and active layers. In all three cases, the systems are assumed to be at steady state equilibrium. In the warmer climate scenario, the active layer has thickened, and the permafrost layer has thinned at both the top and bottom, relative to the initial state (centre). In the cooler climate scenario (left), the active layer has thinned while the permafrost layer has thickened both the top and bottom.

9 Of course, the active layer can thicken slowly, year over year, due to organic debris (branches, leaves, other organic material) deposited on the surface. And as the active layer gets thicker, this can also lead to slow growth of the permafrost layer. We will not consider this mechanism here.

Under a colder environment (left), the permafrost layer has expanded relative to its initial state, into the active layer above and into the frost-free soil below. From a heat flow perspective, we can understand why this would happen over time. The colder surface environment draws additional heat out of the active layer and permafrost, cooling these layers from the top, year over year, until they reach the new steady-state equilibrium reflected in the left-hand figure. Cooling the active layer means the bottom portions of the active layer eventually freeze permanently and are incorporated into the permafrost layer. Thus, the permafrost layer grows upwards, sequestering additional active-layer carbon into the permafrost, making the active layer thinner.

Cooling from the surface also eventually lowers the temperature down through and below the base of the permafrost. This leads to freezing of some of the frost-free soil below, and incorporation of this material into the permafrost layer.

Note that permafrost layer growth does not remove carbon from the atmosphere: this only happens through plant growth in the active layer and subsequent incorporation of plant material into the soil. Permanently freezing the bottom portion of the active layer simply moves already-sequestered carbon from the active layer into more permanent storage.

We can also use this model to explain the impact of higher average surface temperatures. Higher temperatures *reduce* the flow of heat from the active layer into the environment, and transmit heat in the other direction, causing warming of the active layer and, over time, warming of the permafrost. This promotes thaw at the top of the permafrost layer, which in this simple model then adds thawed material to the now-thicker active layer. The warming also permeates downwards through the permafrost, causing thawing at the bottom (where the permafrost is warmest) and adding thawed material to the frost-free layer below. The result, after a few years of gradual change in the thickness of the active and permafrost layers, and once the system is at thermal equilibrium, is a thicker active layer and a permafrost layer thinned at both the bottom and top.

Thawed permafrost adds to and thickens the active layer, making more organic material available for decay, which can lead to increased greenhouse gas emissions. However, increased carbon sequestration in the active layer may partially offset this release, since the warmer environment and a thicker active layer can also lead to additional surface plant growth.

Difference between permafrost and active-layer soil

Although permafrost is described as frozen soil, it is important to realize the two are structurally very different, owing to the processes by which permafrost is created—yearly cycles of freezing and thawing, which, over time, add layers of soil to the permafrost layer. These freeze/thaw processes can cause significant structural changes to the soil, such that the permafrost looks and behaves nothing like the soil from whence it came. Many underlying physical mechanisms play a role in this transformation, such as the expansion of water when it freezes (roughly nine percent by volume), or moisture migration, which in water-saturated soils causes liquid water to migrate towards areas of lower temperature (typically regions rich in ice). Moisture migration, the importance of which depends on soil composition and water content, can lead to separation of water or ice from soil, and to the formation of large ice wedges separate from soil that is frozen but water-depleted: a structure that is then retained vertically in the formed permafrost.

As a consequence of such factors, permafrost structure and composition can vary substantially with depth or moving laterally across the landscape. Importantly, these differences can play a role in determining how permafrost subsequently thaws.

Thus, although Figures 2, 5, and the idealized model they're based on help explain how and why permafrost regions form and remain stable, and how they can respond to changes in surface temperature, the reality of how permafrost forms or thaws over time vary greatly depending on details of soil structure, geography, and moisture content.

Carbon emissions from thaw: Mechanisms and potential mitigation

Permafrost thaw releases organic material that can then decompose to release greenhouse gases. However, abrupt, non-linear thaw mechanisms, per unit of surface area, can have a far bigger climate change impact than gradual thaw because these events release such gases more rapidly and, in particular, release large amounts of methane. This section reviews the two main decomposition mechanisms, to clarify how and why they work.

Broadly put, greenhouse gases are produced by bacterial decomposition of the organic material released when permafrost thaws. Once thawed, decomposition is inevitable—the only questions being *which* greenhouse gases are produced, carbon dioxide or methane, and when and how quickly this happens.

Aerobic decomposition, which takes place in the presence of oxygen, produces the greenhouse gas carbon dioxide. This process occurs in many places, notably over summer in the active layer (tundra surface or a forest floor) where plant droppings and animal waste decompose and are converted into organic materials such as humus. But it can also happen in places where the thawed permafrost material ends up being deposited, such as in lakes, rivers, bogs, mud flats, or taliks, provided there is sufficient oxygen.

Anaerobic decomposition takes place in an oxygen-free environment and primarily produces methane. This takes place in oxygen-deprived locations such as at depth in still-water lakes (including in mud or sediment at the bottom), in bogs, or in permafrost that has thawed but is still buried and isolated from the surface. In particular, anaerobic decomposition is known to take place in taliks, Arctic bogs, and thermokarst lakes, where it emits substantial amounts of methane (Schuur et al., 2015).

Methane production can be naturally mitigated by *methanotrophs*—bacteria that metabolize methane and release carbon dioxide. Such bacteria occur naturally in permafrost environments, and there is much interest in better understanding their role in the emissions process. A recent study of a permafrost region in Sweden found that such bacteria oxidize between 20 and 60 percent of the methane before it could be emitted into the atmosphere (Singleton et al., 2018). But it is unclear if this behaviour is characteristic of all emissions from other, similar permafrost regions.

Thermokarst lakes and regions are not the only potential sources for abrupt methane emissions. For example, in some regions, deep permafrost layers can trap beneath them large pools of methane rising from underground oil and gas deposits. These pools can be released rapidly, suddenly, and in large quantities when the permafrost 'cap' is destabilized by thaw (Birchall et al., 2023).

It may also be possible to modify the active layer to increase atmospheric carbon sequestration. There is recent evidence that simply increasing snow cover can have this effect (DeFranco et al., 2020). Also, by analogy to research on carbon sequestration in agricultural and forest soils (Bossio et al., 2020; Paustian et al., 2019; Post et al., 2004), it may be possible to augment active-layer soils to increase carbon sequestration during the summer growing season.

But, as discussed earlier in this paper, increased snow cover also serves as a thermal insulator, which can lead to ground warming and accelerated permafrost thaw.

This is another reminder of the complexity of the interacting processes that can drive carbon sequestration or greenhouse gas emissions in permafrost regions, and of the importance of research to understand these mechanisms so we can accurately forecast future emissions.

Appendix 3:

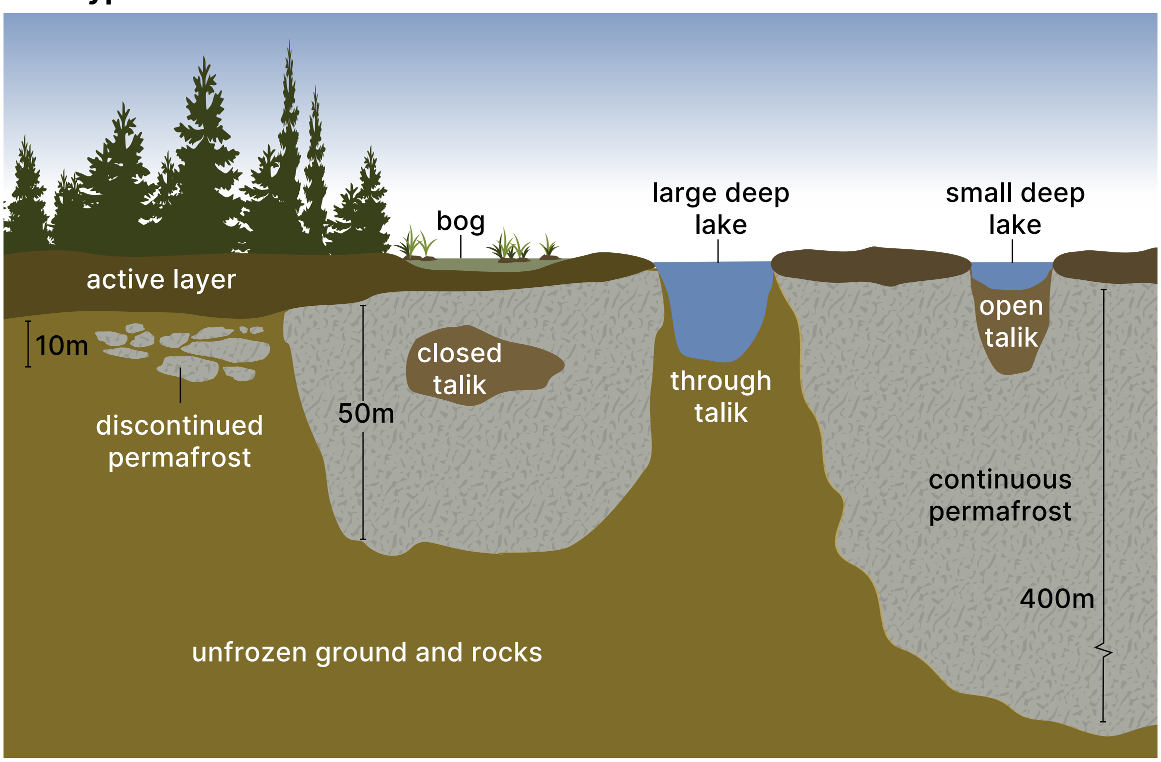
Thaw symptoms and risk factors

As noted in the main text, many factors can impact thaw and its related emissions. For example, thawed permafrost and the active layer, particularly when saturated with water, are mechanically unstable, so subsidence and physical collapse can occur if there is a ground slope or water flow. Such changes can quickly collapse entire hillsides, exposing additional permafrost, leading to additional thaw. This means that geographical features such as lakes, bogs, taliks, or hills can be useful predictors of future rapid thaw (Connon et al., 2018).

Figure 6 illustrates some characteristic geographical attributes of permafrost regions—different types of taliks, and the impact of continuous versus discontinuous permafrost, likely to be helpful in such forecasting.

FIGURE 6:

Schematic relationship between the active layer, permafrost, and different talik types



An illustration of taliks—domains of unfrozen ground embedded in permafrost but that are not part of the active layer. Taliks often form beneath bodies of water (lakes, bogs) and are more common in regions of continuous or discontinuous permafrost. Taliks are important drivers of permafrost thaw. Graphic adapted from Wikipedia contributors, 2025.

There are many other measurable surface properties that may be helpful in forecasting thaw. Some examples are expansion of wetlands, increased or decreased snowfall, changes in topography, changes in local surface temperature, thermokarst formation, and formation of new taliks and lakes—all of which are known factors associated with changing rates of thaw (Devoie et al., 2021). Measurement of these quantities over time could improve the ability to forecast future thaw, and perhaps help identify the most appropriate thaw prevention interventions. The Thermokarst Mapping Collective (Kokelj et al., 2023) represents an initial effort to build an integrated database of such properties across a large permafrost landscape.

Here we summarize some factors known to be associated with permafrost thaw, to give a sense of the complexity of this problem and the richness of potential data. This list is not comprehensive and is intended solely to illustrate the complexity of the relationship between thaw and potential indicators, as well as the opportunity, through aggressive data collection and analysis, to better forecast future thaw.

Note, also, that these factors are not necessarily independent of one another: some may be causally linked. For example, fire can lead to an increase in active layer moisture content or to the growth of taliks, while taliks are known to be causal precursors of thermokarst lakes.

Given the lack of an overarching, functional model for anticipating climate change-driven permafrost thaw, it will be important to monitor as many factors as possible, and to use the information gained to develop models, likely with the aid of artificial intelligence and machine learning, for forecasting and directing thaw mitigation work.

Note also that much useful data can be gathered in real time by remote and satellite-based sensors, such as is available from MDA's INSAR-equipped satellites.

Permafrost thaw drivers:

Surface temperature: Increasing average surface temperature increases likelihood of thaw. Sub-surface temperatures are also useful but will only be available on a small number of experimental sites.

Local weather and climate: Changes in snowfall, rainfall, cloud cover, sunlight, storm intensity, humidity, and other weather events can all impact the likelihood of permafrost thaw, short- and long-term. In particular, increased storm action along lake or ocean coastlines can cause shore erosion, which accelerates thaw, while increased snow depth insulates and warms the ground, as the snow layer blocks heat transfer into the atmosphere.

Surface ecosystem: The nature and health of the surface ecosystem plays a key role in heat transport between the surface and the atmosphere, so changes in the state of this ecosystem play an important role in regulating heat flow.

Fires: Wildfires in forests or tundra are known to accelerate permafrost thaw (Gibson et al., 2018; Kornei, 2020; Yanagiya & Furuya, 2020). They do so by removing or damaging the insulating layer that protects the permafrost from summer warmth and solar radiation. There is also recent work predicting that Arctic warming will lead to an increase in both the number and intensity of fires in subarctic and Arctic regions (Kim et al., 2024), making fire a leading risk for accelerated permafrost thaw (Madaj, 2025).

Taliks: Decomposition inside taliks can emit greenhouse gases (particularly methane), but there is strong evidence that the presence of taliks accelerates thaw in their vicinity, likely due to effective heat conduction channelled through taliks, or due to heat produced in the talik by organic decomposition (Connon et al., 2018; Devoie et al., 2019; Parazoo et al., 2018). Taliks also often coincide with or lie below bodies of water and wetlands, which themselves are factors associated with accelerated thaw.

Bodies of water and wetlands: The warming effect of water accelerates thaw below and near bodies of water and wetlands. Creation of new lakes or wetlands, expansion of existing lakes or wetlands, and increased river water flow are thus good predictors of future or accelerated permafrost thaw.

Thermokarst lakes: Formed as a result of permafrost thaw in predominantly ice-rich yedoma, an organic-rich permafrost formed during the Pleistocene epoch, thermokarst lakes are known to emit large quantities of methane. As the climate warms, these lakes are expanding in both number and size (in ’t Zandt et al., 2020).

Slopes, hills, topography: In uneven or sloped topographies, thawing permafrost can degrade the stability of the terrain, causing the ground—both active layer and permafrost—to slump or collapse downslope, dispersing organic material. Subsequent collapses moving upslope can quickly degrade many hundreds of metres of permafrost.

Active layer composition: Moisture level, state of the biome, layer thickness, soil content, and soil composition all play a role in how well the layer thermally insulates the permafrost, and in resilience against erosion.

Groundcover: Changes in groundcover (the prevalence of bushes, grasses, trees, etc.) can impact the efficiency of ground cooling by changing the surface albedo (proportion of solar radiation reflected away by the surface) or by reducing wind near the surface, which reduces convective heat transfer.

Permafrost composition or type: Factors such as water content, type of organic and non-organic material, and permafrost structure play a role in the occurrence and nature of permafrost thaw. For example, when regions of yedoma thaw, they tend to first form a thermokarst landscape, characterized by an irregular surface of small hummocks and marshy hollows, which evolves as thaw progresses into a collection of thermokarst lakes.

Other surface features: The presence or emergence of surface features such as pingos or thaw slumps can be useful indicators of future thaw (see, for example, Kokelj et al., 2023).

Shore erosion and Arctic sea ice: Shore erosion by storms can expose coastal permafrost, leading to thaw, a process that can be accelerated if sea ice retreats from the coast and exposes the shoreline (Jones et al., 2009).

Appendix 4:

Permafrost glossary

Permafrost science leverages a rich vocabulary arising from many subject areas: biology, geography, geology, chemistry, and more. This appendix explains the permafrost terms used in this paper. For a more complete glossary, we suggest the downloadable, online dictionary prepared by the Canadian Permafrost Association (Lewkowicz, et al., 2024), which uses text, photographs, and figures to explain key ideas.

Active layer: In permafrost regions, the active layer refers to the top layer of soil lying on top of the permafrost layer, which thaws during the summer and freezes in the winter.

Aerobic decomposition: Decomposition that takes place in the presence of oxygen. In this decomposition process, carbon is released mainly as carbon dioxide. Most decomposition in soil is aerobic in nature. Sometimes also called oxic decomposition.

Aerosol: A suspension of fine solid particles or liquid droplets in air. Examples of aerosols in the atmosphere are fog and mist (fine droplets of water) or dust (fine solid particles).

Anaerobic decomposition: Organic decomposition that takes place in the absence of oxygen, for example, in the mud at the bottom of a marsh. Carbon is liberated mainly as methane, although some may be released as carbon dioxide. Sometimes also called anoxic decomposition.

Carbon cycle: The carbon cycle is the natural process by which carbon atoms are constantly recycled between the atmosphere, oceans, soil, and living things.

Carbon sink: Anything that absorbs more carbon from the atmosphere than it releases. Common natural carbon sinks include plants (through plan growth), soil, and oceans. As the climate and local environments change, carbon sinks can become carbon sources, or vice versa.

Carbon source: Anything that releases more carbon into the atmosphere than it absorbs. Common examples are the burning of fossil fuels, or forest fires.

IPCC: The Intergovernmental Panel on Climate Change, the United Nations body created in 1988 to assess the science related to climate change and its impacts.

Methanotrophic (bacteria): Bacteria that eat and decompose methane, emitting carbon dioxide as a waste product. There are many different species of methanotrophs, some living in aerobic environments and others in anaerobic (oxygen-free) environments.

Permafrost: A subsurface layer of soil, typically found in polar regions, that remains frozen throughout the year (technically for a minimum of two years). The layer of soil above permafrost, which thaws in summer and freezes in winter, is called the *active layer*.

Permafrost carbon cycle: The process by which carbon is transferred between the atmosphere, vegetation, the active layer, and permafrost in permafrost regions.

Pingo: A dome-shaped mound in a permafrost area, consisting of a layer of soil over a large hump of ice. Pingos can be quite large: up to 30 metres high and 1,000 metres in diameter. Pingos usually form in a previously drained lake, on top of a talik.

Taiga: Also called a snow forest or boreal forest, a taiga is a biome characterized by coniferous forests of mostly pine, spruce, and larch trees. In North America, taigas cover most of inland northern Canada and Alaska south of the tundra.

Talik: A portion of the ground that remains thawed throughout the year but is surrounded by permafrost, like an island of thawed soil in a sea of permafrost. Often found below a lake or a drained lake.

Thermokarst: A type of terrain found in regions of ice-rich permafrost, characterized by irregular surfaces of marshy hollows and small hummocks that are formed when permafrost thaws. A *thermokarst lake* is a generally shallow body of water that can form in thermokarst-rich regions.

Tundra: A biome where tree growth is severely hindered by persistent cold temperatures and short growing seasons. In the Arctic, one can think of the tundra as existing north of the tree line. Vegetation consists mostly of small shrubs, grasses, sedges (a grass-like flowering plant), mosses, and lichens.

Yedoma: An extremely organic material-rich (roughly 2 percent carbon by mass) ancient permafrost with a high ice content (50-90 percent by volume). Thawing yedoma often leads to thermokarst lake formation and the emission of large quantities of methane.

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