Understanding Permafrost Responses to Climate Change

Dr Christopher R. Burn

A sinkhole near the Dempster Highway in Yukon. It is due to groundwater that now flows beneath the road in summer removing fine particles from the roadbed. Permafrost at the site has thawed due to the influence of the road and climate warming.

Scientia

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It is not just the polar ice caps that are melting. On our warming planet, the ice buried within the layers of ground around the Arctic Circle is thawing, irreversibly changing these spectacular landscapes and posing risks to the communities that call these areas home. Understanding the dynamics of 'permafrost' is vital for predicting its future responses to climate change. The long-term research of permafrost expert **Dr Christopher Burn**, from the Department of Geography and Environmental Studies at Carleton University, Canada, is integral to shaping our collective knowledge of these icy environments.

Revealing Our Planet's Frozen Secrets

In the vast dramatic wilderness of northwest Canada, you could be forgiven for thinking that you are far outside the influence of human activity. But in places on Banks Island and near the western Arctic coast, the ground is quite literally falling apart.

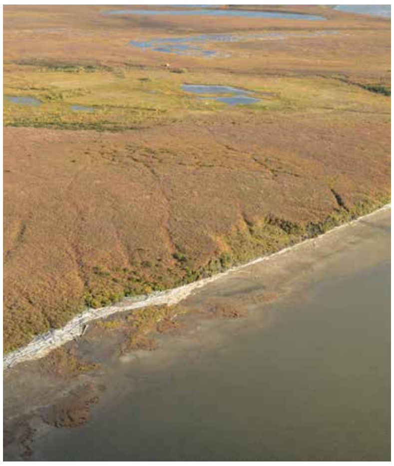
In its simplest terms, this is because rising temperatures and increasing rainfall are causing frozen soils and ice deposits – formed over thousands of years – to melt away. With the icy scaffolding removed, surface soils collapse in on themselves. For people inhabiting these remote regions, permafrost thaw threatens transportation and other public infrastructure, while at the coast enhanced erosion is rapidly removing the ground.

With climate change progressing at an alarming rate, understanding the dynamics and processes behind *permafrost* – ground in and around the circumpolar North and in high mountains that has remained at or below 0°C for at least two consecutive years – is becoming increasingly important.

World-leading permafrost expert and President of the International Permafrost Association, Dr Christopher Burn, has devoted his research career to shaping our knowledge of permafrost terrain. Building on the work of the late Dr J. Ross Mackay, Dr Burn's field research near Mayo, central Yukon, and the Mackenzie Delta area, Northwest Territories, began in 1982. His research includes observations from Illisarvik, the lake experimentally drained by Dr Mackay in 1978, which is the longest continuously monitored permafrost field experiment in North America.

With data collected from remote field sites even in the gruelling depths of the Arctic winter, Dr Burn's long-term research provides field evidence to predict the response of permafrost to future climate change.

His team's research has covered four overarching themes. First, he focuses on understanding the factors controlling the variety of permafrost environments in western Arctic Canada. The second theme aims to elucidate the Earth surface processes that shape the geomorphology of permafrost landscapes. The third focuses on building our understanding of permafrost responses to climate change, and finally, he aims to help manage and mitigate the effect of climate warming on infrastructure in permafrost environments.



The Illisarvik lake basin, Richards Island, Northwest Territories, Canada. The basin was drained on 13 August 1978 in a full-scale field experiment to study the growth of permafrost.

A block of permafrost eroded from the north coast of Pelly Island, Northwest Territories. The active layer is at the top of the ground and below it there is a black layer of organic-rich permafrost. This is an example of the material that may lead to emission of CO_2 or methane.

A 10-metre-high exposure of ice-rich permafrost near Mayo, Yukon. The uneven texture is from veins and lenses of ice. The horizontal line separating the light-coloured ground from the dark material represents the deeper active layer of the early Holocene climate optimum.

'The ultimate justification for the research is to assist regulators of development projects and operators of public infrastructure to identify and manage risks to new facilities and the transportation network posed by climate change and ground-ice dynamics,' explains Dr Burn. His research helped to inform the public review of the proposed Mackenzie Gas Project (2003–2010) and development of the all-weather road between Inuvik and Tuktoyaktuk in the Northwest Territories (2012–2017).

Permafrost Structure

Permafrost terrain consists of an 'active layer' – or seasonally thawed layer – underlain by perennially frozen ground. Permafrost varies in thickness between regions from a few metres in southern Yukon to over 600 metres near the western Arctic coast, 1000 kilometres further north. The differing depths reflect the varying ground conditions controlled by climate, with a mean annual ground temperature of around −1°C in southern Yukon, and around −7°C at the coast. Dr Burn's research has captured data from sporadic discontinuous permafrost, where only 20% of the surface is underlain by perennially frozen ground, to continuous permafrost in the western Arctic, where permafrost is ubiquitous.

Long-term observations from the Illisarvik site have shown that the active layer in Canada's Arctic is growing steadily thicker in response to climate warming. In other words, the depth of seasonal thaw is increasing with each passing year. By 2018, the active layer in tundra near Illisarvik was 10 centimetres deeper than 35 years prior. The deepest available measurements show temperature changes in permafrost since 1970 extending to depths of 53 metres, while calculations suggest the warming has reached 120 metres depth. The ground warming has been accompanied by subsidence of the surface, at rates measured near Illisarvik of over 3 centimetres per year since 2006.

Although permafrost is defined purely in terms of temperature, the ice content controls the loss of structural integrity when such ground thaws and its deformation when it freezes. Permafrost ice may consist of veins and lenses of various sizes interspersed with soils and rock or bodies of massive ice. Some of these massive ice bodies have survived since the last Ice Age, and are only now becoming exposed. Other ground ice has developed in the soil itself, forming lenses that are millimetres to centimetres in thickness.

The distribution of ground ice shapes the permafrost landscape. *Thermokarst* describes terrain with ditches, marshy hollows and lakes, formed as ice in the ground melts. The occurrence of thermokarst, especially large thaw slumps, is increasing in the western Arctic.

Because the structure and dynamics of permafrost vary greatly across spatial scales, Dr Burn's investigations have spanned from the sub-millimetre scale – such as the movement of water through soil pores towards the freezing front – through to scales of thousands of kilometres. Investigating such large scales is necessary for understanding the original development of permafrost in the tectonically active setting of northwest Canada.

A Hidden Threat

Thawing permafrost has consequences more insidious than slumping ground damaging infrastructure and the beauty of the natural landscape. Permafrost formation halted many natural processes in these soils, such as vegetation decomposition, effectively trapping carbon, which would otherwise have been released into the atmosphere as carbon dioxide or methane. As the permafrost thaws, this carbon can now be released to enter the global carbon cycle, enhancing the greenhouse effect and contributing to climate warming.

Dip in a road surface near Tuktoyaktuk, Northwest Territories. Only two weeks before this photograph was taken the road had been levelled. The subsidence is due to melting of ground ice below the road.

Permafrost ranges in age from a few tens of years to hundreds of thousands of years old. Some of the oldest permafrost ice discovered, from Dominion Creek in the Klondike gold fields of Yukon, is around 750,000 years old. As such, thousands of years' worth of carbon could be lurking beneath the surface like a ticking time bomb. The thawing process could lead to a devastating positive feedback loop – as more carbon escapes throughout the circumpolar North, climate warming is accelerated, causing more permafrost to thaw and release more carbon, and so on. Most permafrost carbon is contained in the uppermost 2 metres of permafrost, meaning that its release may begin relatively soon, potentially over the next century.

However, much of the world's deep permafrost has survived the warmer periods in between the colder glacial periods of the planet's history. Dr Burn's research examining the dynamics and response of permafrost helps to quantify the risks. He has examined timescales ranging from epochs – more than three million years – through to thawing patterns within a single season. 'Integration of processes active at these different scales is required not only to understand the genesis of the landscape, but also the response of the landscape to thawing,' he explains. In the early Holocene, about 9,000 years ago, active layers were about 1 metre thicker in the western Arctic than at present, partly due to a warmer climate and partly because the coast and the cooling influence of the ocean were a further 50–100 kilometres north of their current location.

Dr Burn's work on the patterns of climate warming also suggests that the magnitude of changes across permafrost terrain may not be uniform. Although annual mean air temperatures have increased across Canada since 1970, in the western Arctic the rate has been 0.75°C per decade, while in other areas the rate is lower. In southern Yukon, for example, the increase is about 0.45°C per decade. Adding a further layer of complexity, these increases have not been uniform across all seasons, with warming particularly significant during the autumn and winter months. Nevertheless, conditions similar to the early Holocene may reoccur before the end of this century.

Putting Research into Practice

Permafrost research in many countries is a relatively new. According to the *Web of Science*, before 1990 fewer than 60 research papers in permafrost science were published in peer-reviewed journals each year. A surge in permafrost research since then, especially in the last 15 years, has led to this number reaching over 1800 articles per year by 2020. This increase in interest was partly catalysed by the International Polar Year of 2007 to 2009 – an extended observation period allowing for a complete annual cycle in both the Arctic and Antarctic regions – with coordinated study of the polar regions by scientists from across the world, but also by the widespread interest in the changing Arctic. Because of permafrost science's short history, Dr Burn's field evidence spanning more than 40 years is remarkably valuable and unique.

Building positive relationships with First Nations people and Inuvialuit field partners has allowed Dr Burn to collect data from remote field sites during the inhospitable and treacherous winter months. Only residents can provide valuable observations year-round. 'The field observations we have reported from these sites will remain foundational information for the region, because it is most unlikely that new programs will be sustainable in such areas in the next few decades,' says Dr Burn.

Mitigating the risks to infrastructure and communities in these Arctic and sub-Arctic permafrost regions posed by a changing climate requires the regional geographic knowledge and perspective offered by Dr Burn's work. 'However, to be effective, this information must be available and useful to engineers, planners, and others who are responsible for implementing adaptation projects,' he says. In addition to his collection of published research papers, Dr Burn has also made his approach and findings available to non-specialists by authoring two books.

With the dynamics of permafrost terrain likely to switch from being dominated by freezing to being dominated by thawing over the coming decades, Dr Burn's research is going to become increasingly significant. Although halting the devastating effects of climate change may be an impossible goal, the work of researchers like Dr Burn may help northern residents, communities, and agencies adapt to the inevitable difficulties.

Meet the researcher

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Having completed his undergraduate degree at the University of Durham, UK, Christopher Burn moved to Canada, earning both his master's and doctorate from Carleton University. He currently holds the position of Chancellor's Professor at Carleton University's Department of Geography and Environmental Studies, and is also the President of the International Permafrost Association. Dr Burn's commitment to long-term field investigations has helped to shape our understanding of permafrost. His research interest is particularly focused on the relationship between permafrost and climate, providing valuable tools to predict the response of these terrains to future climate change and to ensure the continuing integrity of infrastructure built on permafrost. In 2018, he was awarded the Canadian Polar Medal and a DSc by Durham University for his contribution to permafrost research. In addition to his research activities, Dr Burn also devotes time to supervising Carleton University's Graduate Programs in Northern Studies, and lecturing on permafrost.

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FURTHER READING

CR Burn, AG Lewkowicz, MA Wilson, Long-term field measurements of climate induced thaw subsidence above ice wedges on hill slopes, western Arctic Canada, Permafrost and Periglacial Processes, 2021, 32 (in review).

CR Burn (editor), Herschel Island Qikiqtaryuk:A natural and cultural history of Yukon's Arctic island. Whitehorse: Wildlife Management Advisory Council for the Yukon North Slope and University of Calgary Press, 2012.

CR Burn, SV Kokelj, The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes, 2009, 20, 83–105. DOI: 10.1002/ppp.655

CR Burn, Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada. Canadian Journal of Earth Sciences, 2002, 39, 1281–1298. DOI: 10.1139/e02-035

CR Burn, Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada, Canadian Journal of Earth Sciences, 1997, 34, 912–925. DOI: 10.1139/e17-076