of field data due to difficulties in measuring CO_2 flux during winter and poor spatial coverage because of access challenges in this remote region. Field measurements are the most direct method for quantifying CO_2 flux and can be combined with other types of data, such as observations from satellites, to scale values up from individual sites to broader regions. Field data are also essential for developing and benchmarking the simulation models used to predict current patterns and future change.

The Arctic is increasingly recognized as a vital link in the global carbon cycle, and CO_2 flux from permafrost sites is being tracked more closely as methods and equipment improve (see Fig. 1) and monitoring networks expand. Natali et al.[2] compiled winter CO_2 flux data collected from more than 100 sites in the pan-Arctic permafrost region and evaluated factors that influence carbon degradation in the winter. They identified important environmental and ecological controls on winter CO_2 production (such as air temperature, soil temperature, soil moisture and vegetation type) from weather maps and data obtained from satellites. This information was then used to estimate how much CO_2 is emitted annually from the entire Arctic permafrost region.

The contemporary winter CO_2 loss of 1,662 TgC that Natali and colleagues[2] report is higher than previously published values. This new estimate is noteworthy because it exceeds the estimated 1,032 TgC taken up by vegetation during the growing season, suggesting that the region is a source of carbon to the atmosphere and therefore contributes to further warming. To take this a step further, the authors used a model to simulate how winter CO_2 emissions in this region might change in the future. Their analyses reveal that carbon loss during winter could increase by as much as 41% by the end of the century under the most extreme climate change scenario, and by 17% under a more moderate scenario that includes mitigation strategies.

Although the new estimate of winter CO_2 loss from the Arctic permafrost region is based on the best available data, the uncertainty in the value is large (813 TgC). Part of this uncertainty is due to the variety of methods used to measure CO_2 and could be improved by standardizing protocols. Increasing the spatial coverage and density of sites where CO_2 is measured year-round would also reduce the uncertainty, as would improvements to the remote sensing data used to model emissions across the region. Despite the uncertainty in the estimate, high winter CO_2 losses from Arctic permafrost have important implications for the carbon balance. Recently, there has been much emphasis on 'Arctic greening' — warming-induced increases in vegetation that enhance carbon uptake[8]. Results from the study by Natali and colleagues suggest that increases in the vegetation carbon sink could be offset by higher losses of CO_2 during winter.

Quantifying CO_2 emissions from the Arctic permafrost region is essential for evaluating climate feedbacks that influence the magnitude of future warming. Winter is often considered a period of dormancy with little biological activity, so the large loss of CO_2 reported by Natali and colleagues[2] during this season is surprising and alarming, given that CO_2 emissions are expected to increase as temperatures continue to rise. Although it is challenging to measure winter CO_2 flux, these data are key to understanding the impacts of the dramatic changes that are occurring in this rugged, yet remarkably vulnerable landscape. ❐

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ARCTIC HYDROLOGY

Engineering challenges of warming

Observations reveal recent Arctic warming, but future societal impacts are poorly understood. Now research identifies potential abrupt thaw-driven soil moisture shifts, with consequences for northern development including more intense wildfires and rainfall.

Barret L. Kurylyk

In Arctic landscapes, ground temperatures control water flow and storage because frozen ground is relatively impermeable. Subsurface water flow in cold regions is predominantly restricted to a seasonally thawed zone that maintains wet shallow soil conditions[1]. In contrast, in warmer sub-Arctic regions, the deeper summer thawed zone allows for a deeper water table and drier near-surface soils. Hydrologists studying northern water resources must therefore consider how climate change will affect subsurface temperatures and water flowpaths. Writing in *Nature Climate Change*, Bernardo Teufel and Laxmi Sushama[2] show that Arctic permafrost thaw may lead to a rapid transition between regimes with shallow or deep thawed zones (Fig. 1), drying soils and causing cascading environmental impacts.

Permafrost (ground that remains below 0 °C for at least 2 years) does not reach the land surface, because shallow soil warms above 0 °C in the summer. This shallow zone, known as the active layer, experiences seasonal freezing and thawing and separates the permafrost table from the land surface (Fig. 1). Darcy's Law, the foundation of hydrogeology, states that groundwater flow is proportional to the hydraulic conductivity, a measure of permeability. When the active layer thaws in the summer, its hydraulic conductivity can increase by up to 10 million times[3], opening subsurface flow pathways that remain closed in the winter.

Multidecadal hydrological changes are superimposed on these seasonal changes. As the climate warms, permafrost responds by first warming to the freezing temperature

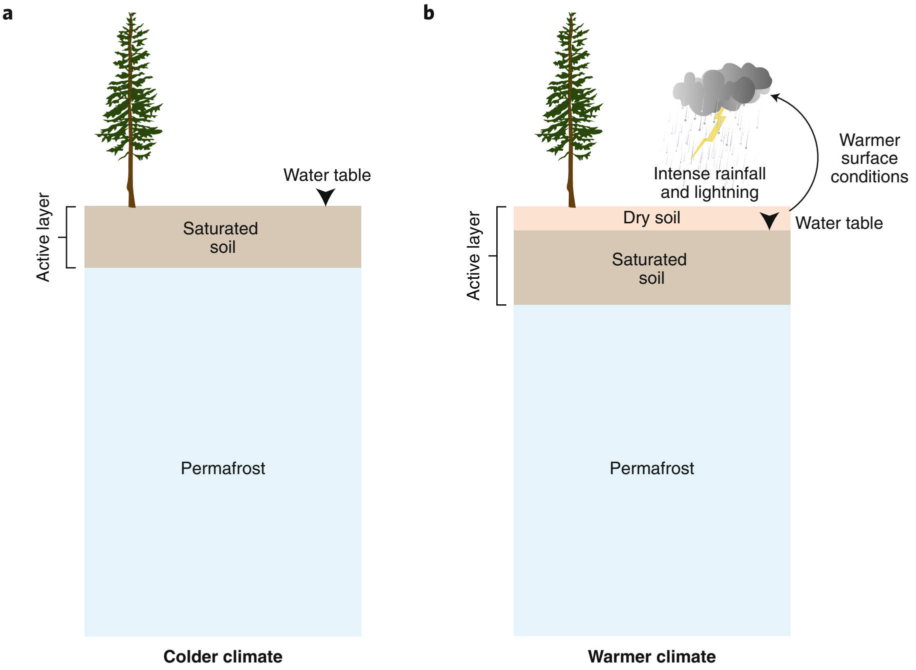

Fig. 1 | Schematic of processes triggering Arctic regime shifts. a, As detailed by Teufel and Sushama[2], when the summer thawed zone (active layer) is thin, the water table is close to or at the land surface, creating wet surface conditions. **b**, As the climate warms, the active layer thickens, and this can suddenly dry near-surface soils, causing warmer surface conditions, soils with reduced strength, convective rainstorms and lightning.

and then thawing. Downward permafrost thaw results in a thickening of the active layer (Fig. 1b), allowing for deeper flowpaths and more water storage[4]. Permafrost warming and thawing are already occurring across the pan-Arctic[5,6] and are expected to accelerate in the future[7]. Consequently, a widespread restructuring of subsurface hydrology will occur at different scales as the active layer thickens and as wetlands become connected to rivers. In essence, more water will be stored and routed through the subsurface as groundwater, rather than being stored in wetlands or flowing along or close to the land surface. Although Arctic climate warming is occurring at an amplified rate, permafrost thaw and associated hydrological changes are conceptualized as gradual processes, owing to the substantial thermal energy required to thaw frozen soil.

Teufel and Sushama[2] advance the field of climate change science and engineering by moving beyond this assumption of slow trends and pointing instead to the potential for abrupt changes triggered by permafrost thaw. The authors use a state-of-the-art climate model for the pan-Arctic to demonstrate that once downward permafrost thaw crosses a critical threshold, the permafrost no longer functions as a dam that controls subsurface water storage and movement. Before this threshold is reached, the soil moisture near the land surface is high, but afterwards the near-surface soil will rapidly dry as drainage is facilitated.

These findings have wide-reaching, multidisciplinary implications. Ecosystems will respond rapidly to soil drying, with plant vulnerability dependent on root depth. Changes to soil moisture as well as the permafrost depth will have an impact on soil strength, creating new challenges for geotechnical engineers designing roadways and foundations. Furthermore, streamflow during the snowmelt season will decrease because of greater water storage capacity in a thicker active layer, yet streamflow may increase during the warm season as the active layer continues to release groundwater to rivers. This increased flow in the warm season may in turn increase the risk of flooding during heavy summer rainfall, suggesting that engineered infrastructure for conveying water should accommodate abrupt future changes.

The results also reveal future ground surface warming caused by the shift towards drier soils. Warmer surface soil layers will lead to unstable atmospheric conditions and trigger intense, short-duration rainfall from convective precipitation events, whereas large-scale precipitation will decrease. Changes to the rainfall regime could affect soil hydraulic properties[8] and would further exacerbate the summer flooding issues noted above. Finally, because lightning and convective precipitation events are related[9], abrupt soil moisture shifts could cause more lightning strikes (Fig. 1b). When these are combined with the increased combustibility of regions with drier soils, more frequent and intense wildfires could occur.

The study interprets the impacts of abrupt environmental changes in the context of new challenges facing northern development and engineering. In general, engineers have lagged scientists in considering the consequences of future climate change. Just as social science is now recognized as a key part of climate change research, it is likewise critical that future climate change science begin to integrate engineering to translate study results and promote sustainable development with adaptive capacity. It is also important to note that the study's findings are derived from climate model projections from one scenario of future greenhouse gas conditions. More northern monitoring is needed to ground such modelling in observational data.

Design practices with adaptive capacity would have to be implemented in the near future to address these engineering changes. To highlight this adaptation paradigm shift, Teufel and Sushama[2] point to the need for decision-makers to advance beyond planning for gradual change and rather accept the potential for sudden environmental regime shifts and related development challenges.

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