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Short Communication

On the (melting) rocks: Climate change and the global issue of permafrost depletion

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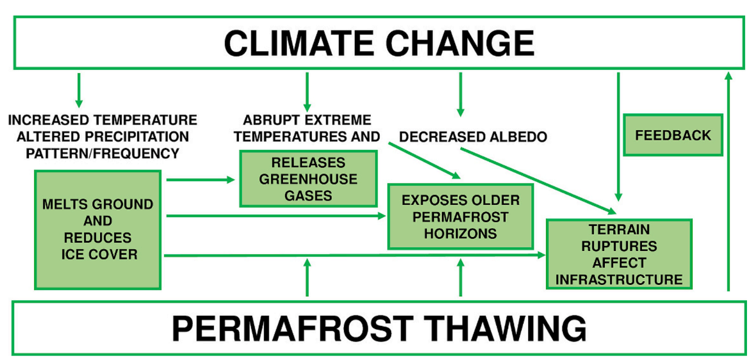
HIGHLIGHTS

- Permafrost thawing is associated with climate change and demands global solutions.
- Permafrost thawing impacts global climate, sustainable development, and CO_2 budget.
- Permafrost thawing disrupts hydrology, habitats, forest cover, and infrastructure.
- Thawing older permafrost horizons can release GHG and locked nocive components.
- More research is needed to better understand the impacts of permafrost depletion.

GRAPHICAL ABSTRACT



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ABSTRACT

This short communication reports on the pressures posed by climate change on permafrost. The phenomenon of the (melting) rocks, soil, and ground that host permafrost does not just concern a remote stretch of the Arctic north. It is a far larger area than most citizens may realise if looking at an ordinary map projection. Broadly distributed and crucial as it is for the Earth's climate, permafrost thawing due to climate change can affect or upend several aspects associated with life and prosperity on Earth, demanding far greater attention. The loss of permafrost is a global problem that requires a global solution. Greenhouse gas emissions (GHG) must be reduced to slow permafrost's thawing and negative impacts. As such, this short communication aims to catalyse a global debate on this climate change consequential issue, also providing specific suggestions for reducing the impacts of permafrost depletion.

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1. Introduction

Permafrost is essential in the Arctic region as it plays a significant role in undergirding the ground, thus supporting infrastructure and countering erosion, which can be globally impactful (Beer et al., 2020; Larsen et al., 2021). In addition, permafrost is vital in storing carbon. However, the Arctic has experienced increased temperatures in the past few decades, driving permafrost to thaw and releasing greenhouse gases (GHG) into the atmosphere (Schuur et al., 2022). The thawing of permafrost has large-scale environmental implications and impacts the economy and culture of coastal communities and beyond (Beer et al., 2020; Intergovernmental Panel on Climate Change (IPCC), 2022; Lamoureux and Lafreniere, 2018). Fig. 1, produced by the European Space Agency's (ESA) Climate Change Initiative (CCI) permafrost project (Obu et al., 2021), shows the spatial distribution of permafrost active layer thickness across the northern hemisphere.

The intensive, ubiquitous burning of fossil fuels since the mid-1800s has led GHGs to spike in the atmosphere, which is responsible for the permafrost melt in various areas, including the Arctic (Friedlingstein et al., 2019; Schuur, 2016). Between 2007 and 2016, for instance, the ground temperature near the depth of zero annual amplitude – i.e., the depth at which annual temperature fluctuations are dampened to less than 0.1 °C – in the continuous permafrost zone increased by 0.39 ± 0.15 °C (Biskaborn et al., 2019).

Due to decreasing ice cover over most Arctic regions, the 'snow-ice albedo feedback' has been affected. As a result, less solar radiation is reflected, and more heat is absorbed on the surface, causing further warming and thus increasing permafrost thawing (Riihelä et al., 2021).

Permafrost contains carbon-based organic matter, consumed by microorganisms whenever it thaws, releasing methane (CH_4) and other gases (Masyagina and Menyailo, 2020), which, in turn, impacts microbial communities (Lamoureux and Lafreniere, 2018). Moreover, the current permafrost thaw will likely intensify under this century's projected global warming and the release of substantial amounts of GHG, exacerbating the problem (Schuur et al., 2015). Since soil respiration responds to warming more strongly in colder climates than in warmer ones, these emissions are of particular concern (Carey et al., 2016), resulting in increased CO_2 emissions and CH_4 (Grant et al., 2019), thus intensifying climate change.

Moreover, wildfires' increasing occurrence and broadening (Kasischke and Turetsky, 2006) are powerful yet underestimated stressors in fragile permafrost contexts (Gibson et al., 2018).

2. The impacts of permafrost thaw

Continuous and discontinuous permafrost covers about 15 % of the land surface in the northern hemisphere (Smith et al., 2022; Obu, 2021). This figure highlights the urgency of addressing climate change and protecting permafrost. Retreating and spatial shifting in the distribution of frozen ground alters the forest cover, hydrology, species habitats and human life in the areas affected (Czerniawska and Chlachula, 2020). The thawing of permafrost not only exerts consequences on terrain, ecosystems and infrastructure but may also delay or impair international efforts concerning sustainable development (Hjort et al., 2022; Leal Filho et al., 2022, 2023) and CO_2 abatement (Schuur et al., 2022; Turetsky et al., 2019), influencing the various climate scenarios (Intergovernmental Panel on Climate Change (IPCC), 2022). Fig. 2 captures some of the multi-faceted, diverse impacts of permafrost depletion.

The anatomy of the rock and sub-soil structure involved in how permafrost unfolds and the spatial extents, geometry, and shallow-seated mechanism of how the affected terrain ruptures due to thawing (Smith et al., 2022) unveils a peculiar shallow behaviour. For instance, thawing has waned the concrete integrity of the ground/foundations where infrastructure has been built over the decades (Hjort et al., 2022; Langer et al., 2023). Threats to existing infrastructure related to permafrost thawing include active layer thickenings and thaw-related

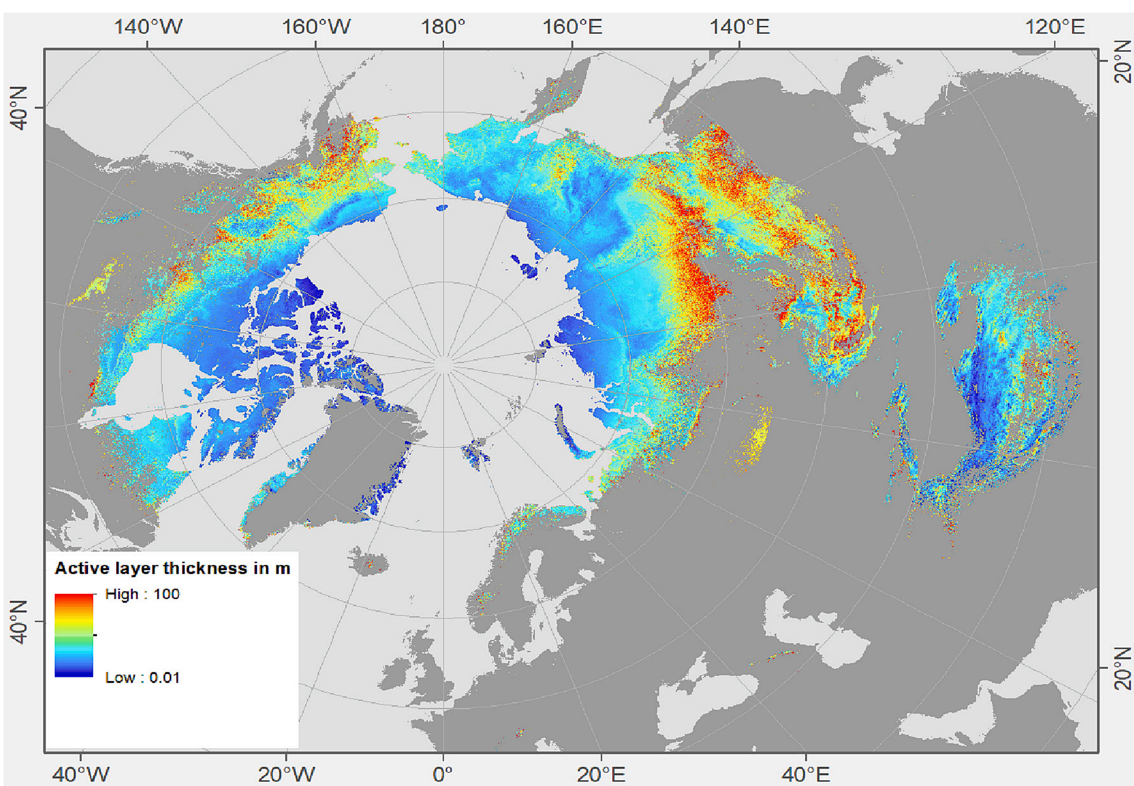

Fig. 1. Permafrost active layer thickness for the Northern Hemisphere, v3.0 from MODIS LST, ERA5, 1997–2019. Source: AWI, Germany (https://apgc.awi.de/dataset/permafrost-cci-alt-north-hemisphere-v3-1997-2019).

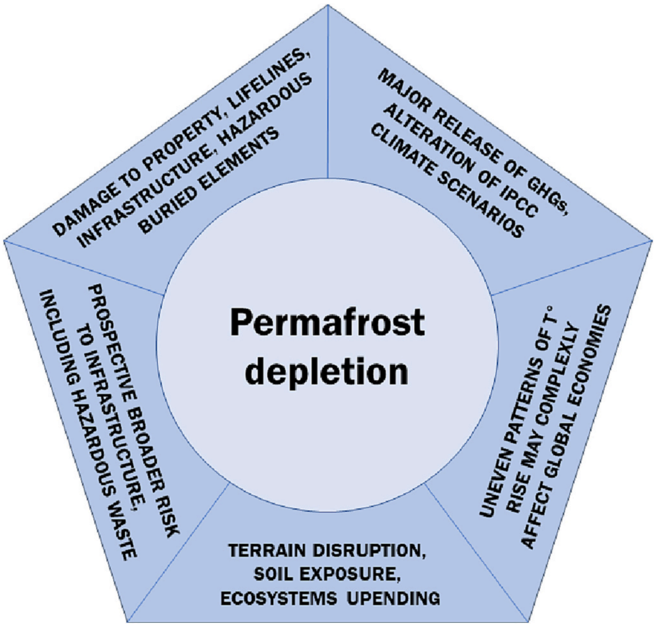

Fig. 2. Physical and geophysical consequences of permafrost depletion.

hazards, such as thermokarst and mass wasting (Schuur, 2016; Schuur et al., 2015).

The risk of permafrost-related degradation will likely increase significantly by 2050, with infrastructural impairment already documented in swaths of Russian territory, where many buildings and legacy fuel storage facilities are experiencing damage and whose leakage (e.g., of old Soviet-era fuel storage tank ruptures) may pose a further threat to the environment as well (Langer et al., 2023; Wrigley, 2023).

For example, in the Qinghai-Tibet Plateau, 30 % of roads were reported to have been affected (Hjort et al., 2022). In addition, the risk of structural damage and leakage of hazardous waste is projected to be very significant over the following decades, whatever the reference climate scenario (Langer et al., 2023).

Apart from causing terrain rupture and ensuing damage to the built environment, permafrost thawing has been driving vast alterations to the natural landscapes of the northern regions since the 1960s (Turetsky et al., 2019). In high-altitude areas hosting glaciers, rapid transformation due to permafrost degradation has led to the onset of new lakes and drainage networks, with ensuing reduced slope stability that may further trigger flooding due to mobilised deposits and water mass (Haeberli et al., 2017), ultimately adding potential strain to infrastructure and human life in the exposed regions.

The thawing of permafrost also releases chemical, biological and radioactive components that have been locked under various forms in both the cryosphere and the geosphere over the 10^3–10^5 yr span, resulting in vast disruptions of ecosystems, altered wildlife populations and prospective endangerment to the human health (Intergovernmental Panel on Climate Change (IPCC), 2022; Miner et al., 2021).

Permafrost thaws at different rates (Intergovernmental Panel on Climate Change (IPCC), 2022), and slower thawing tends to affect the shallower, more recently frozen layers of soil, rock and ice, penetrating the deeper sections of permafrost. However, abrupt thawing, capable of dismantling whole rock and soil sections, affects older, deeper layers (Turetsky et al., 2019). While the thawing phase depends on temperature and precipitation changes and may occur gradually, the rate increases as temperatures are consistently higher – all the more in Arctic regions – and vast areas and volumes of permafrost can be lost per decade (Turetsky et al., 2020).

3. Moving forward: addressing an issue more global than commonly perceived

The rapid depletion of permafrost in the Arctic threatens efforts to reduce global warming. In addition, it heightens climate change in other regions (Intergovernmental Panel on Climate Change (IPCC), 2022; Masyagina and Menyailo, 2020) to the extent that may elude – both in space and time – the assumed geographic boundaries of cold permafrost regions "up North". Despite ample literature, this has contributed to a somewhat slow and sparse perception throughout societies of the phenomenon, its long-time onset, and its cascading spatial effects (Intergovernmental Panel on Climate Change (IPCC), 2022).

Abrupt thawing occurring through extreme temperature fluctuations can expose older permafrost horizons more rapidly than earlier estimated. Depending on local conditions and the rock and soil fabric involved, such a phenomenon may initiate the release of compounds from deeper layers much faster than expected (Turetsky et al., 2019). There are also concerns that permafrost degradation will eventually expose ancient burial sites, thus possibly reviving vectors that, under present-day temperature conditions, could spread deadly infections or allow the re-emergence of pathogens, thus potentially endangering human health (Huber et al., 2020). Therefore, actionable, effective solutions are needed to slow down the rate at which permafrost thawing grows – including the engagement of the public discourse.

Some of the measures which may help to handle permafrost thawing are:

i) **Installing permafrost insulation** to shield permafrost from the heat of the sun and other environmental factors affecting the terrain's integrity. This could include insulation boards and thermal blankets around buildings, pipelines, and other structures built on permafrost.

ii) **Planting more cover crops** can help to keep permafrost cool and stabilise the ground. Perennial grasses and trees can provide shade, which can help reduce the permafrost thaw rate. In addition, these plants may help to keep the soil moist and add organic matter to help improve the soil quality.

iii) **Facilitating groundwater recharge** can help keep permafrost cool and reduce the thaw rate. This can be attained by constructing rainwater harvesting systems and using porous pavings to increase the amount of rainwater stored in the ground.

iv) **Improving snow cover** can help keep permafrost cool and reduce the thaw rate. This can be done by planting trees and shrubs to create shade or using snow fences to accumulate snow and reduce the speed at which it melts.

Permafrost melting is an urgent environmental issue, as it can contribute to global warming and impact the environment in a diverse range of issues across vast regions. Reducing GHG emissions to address this issue, a critical driver of permafrost melting, is crucial. It is also essential to understand the local impacts of permafrost melting, such as increased flooding, erosion, and water and soil contamination. In some areas, protecting infrastructure, ecosystems, and communities from the effects of permafrost melting becomes necessary.

In summary, the depletion of permafrost is a serious problem because it has several negative impacts. For example, it can:

- Destabilise infrastructure, such as roads and buildings.
- Increase the risk of flooding and landslides.
- Release CH_4, a potent GHG, into the atmosphere.
- Disrupt ecosystems and food webs.

Therefore, GHG emissions need to be reduced to slow the thawing of permafrost and reduce its negative impacts.

Finally, it is vital to monitor permafrost more intensively to detect early signs of melting and ensure appropriate measures can be taken promptly.

CRediT authorship contribution statement

All authors have equally contributed to writing this short communication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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