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Permafrost ground ice modulating soil carbon emissions

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Permafrost ground ice, encompassing all ice forms within permafrost, serves as a crucial solid water reservoir in cryospheric regions. Its rapid melting is intensifying with profound consequences for the carbon cycling. Thawing of permafrost ground ice triggers substantial geomorphic shifts, stimulate the growth and metabolism of microbes, and accelerate carbon cycling—processes that will shape carbon dynamics in the coming decades. Herein, we emphasise the urgency of studying permafrost ground ice to understand the mechanisms of carbon storage and release. Our findings aim to clarify the balance between carbon sources and sinks in permafrost regions, offering critical insights for predicting climate feedbacks during ongoing and future climate warming.

INTRODUCTION

Permafrost is ground that remains at or below 0°C for at least two consecutive years, especially containing large amount of ice content.[1,2] It is widely distributed in high-latitudes (e.g., Arctic) and high-altitudes (e.g., Tibetan Plateau, TP) regions. Usually, permafrost with relatively high ice content (>20% by volume) is mostly found across high-latitudes, while lower-ice-content (<10%) dominates in mountainous region and high plateau areas.[2] Crucially, permafrost stores a substantial amount of soil organic carbon (SOC) approximately 1014 Pg C within the top 3 meters of northern Hemisphere permafrost soils.[3] This carbon accumulates over millennia due to cold temperature and slow decomposition of plants and animal remains. Besides, abundant ice content in permafrost is a key regulator on the impact of regional carbon cycle in a changing climate.

As permafrost thawing—driven by continuous climate warming and heat absorption during the ice-to-water phase change —microbes gain the capacity to decompose the previous frozen SOC entrapped in permafrost due to the deepening of active layer and occurrence of thermokarst processes. Thawing permafrost releases significant amounts of carbon dioxide and methane into the atmosphere, increasing atmospheric greenhouse gases concentrations and exacerbating global warming.[4] Permafrost degradation also disrupts water systems including cryospheric hydrology, ecology, and biogeochemistry, threatening regional and global environmental sustainability.[5]

Permafrost acts as an early indicator of climate change and potential sources of carbon emissions, making it critical for global emission reduction policies and carbon neutrality goals. Recent studies show that soil moisture and elevation are the primary drivers of SOC storage in permafrost regions, whereas surface temperature (in the Arctic region) and precipitation (on the TP) are important climatic constraints on SOC reserves.[3] These differences reflect the Arctic's cold region, relatively low temperature and relatively high ice content, versus the TP's high altitude, sparse vegetation coverage, diverse sedimental types and complicated topographic features. However, most research has focused on the SOC of the active layer (the layer above permafrost that freezes and thaws annually, typically melting in summer and freezing in winter) in permafrost regions,[5] leaving deep-layer permafrost poorly understood. Models predicting carbon dynamics show significant discrepancies, highlighting ongoing bias in our understanding of carbon climate feedbacks.[3,4] The strong spatial heterogeneity of the distribution of ground ice and the complexities of energy exchange during the ice-water phase transition further complicate carbon budget estimates.[2] There is a pressing need for SOC observational data from deep-layer permafrost, especially for the ground ice.

Critical role of permafrost ground ice in carbon dynamics

Permafrost ground ice refers to all forms of ice embedded within permafrost, acting as a crucial solid water reservoir in cryospheric regions. It is ubiquitous and widespread in permafrost regions, ranging from shallow depths (0.5 m) to over 100 m below the surface. This ice takes many forms, ranging from soil pore ice, centimeter-scale ice lenses and networks, up to massive networks of ice of fine-grained sediments and soils that restrict water drainage.[2,6] Despite this prevalence, we know a little about the exact distributions or composition of permafrost ground ice. Extensive permafrost degradation alters hydrological processes and can release legacy carbon, nitrogen, and pollutants. Permafrost ground ice is prone to rapid thawing and the associated deep mobilization of SOC. Owing to the presence of ground ice, the carbon cycle of permafrost soils differs from that of other soils. However, the lack of data on ground ice distribution and related carbon stocks at various depths within the permafrost hinders the understanding of the permafrost carbon budget, leading to significant uncertainty in predicting future impacts and risks of permafrost thawing. Given the invisibility of ground ice and the nonuniformity of its melting processes, there are still significant uncertainties regarding hydrology, water resource availability, and changes in permafrost regions, which substantially affect permafrost SOC stocks.

Challenges in understanding permafrost carbon budgets

Current methods of detecting permafrost ground ice—such as manual drilling and pit exploration, are inefficient and provide point scale localized data. This limits our ability to estimate ice volumes accurately and introduce large uncertainties of permafrost ground ice estimations. For example, estimates of the International Permafrost Association for the Northern Hemisphere permafrost ground ice volume ranged from 5.63×10^3 to 15.12×10^3 km^3, while the alternative calculations suggest volumes up to approximately 11.37×10^3 – 36.55×10^3 km^3.[2] For the TP, known as the Asian Water Tower, the estimated total permafrost ground ice reserves are approximately 12.7×10^3 km^3 with a permafrost area of 1.06×10^6 km^2.[7] Unlike high-latitude permafrost, the high-altitude permafrost on the TP is more sensitive to the air temperature rising and human activities, leading to rapid degradation under continuous climate warming. Remote sensing and unmanned aerial vehicle analysis show that melting ground ice accounts for approximately 70% of the volume loss during permafrost collapse on the plateau,[8] releasing substantial amounts of organic carbon into the aquatic environment and the atmosphere. A recent study has suggested that the dissolved organic carbon (DOC) in exposed ground ice is approximately 100 mg L^{-1}, which is considerably higher than that in precipitation, river water, and glaciers in the region.[8] DOC concentrations (9.7–21.5 mg L^{-1}) in deep permafrost ground ice (4.8 m in depth) in northeastern TP revealed substantial enrichment, by a factor of 7.0–36.0, relative to the other water elements on the TP.[9] In Arctic regions, yedoma deposits (ice-rich permafrost) holds up to 90% ice by volume and store more carbon than any other permafrost stratum per square meter. Meanwhile, atmospheric CO_2 emissions from thawing yedoma in the southern part of the Laptev Sea area varied from 9 to 439 mmol m^{-2} day^{-1}, suggesting that the eroded coastal area served as a more significant source of CO_2 to the atmosphere than the tundra on the neighboring Primorsky coastal plain.[10] Consequently, a large amount of bioavailable carbon in the ground ice can be released into the aquatic and atmospheric environment under continuous warming conditions. Rapid permafrost degradation (e.g., collapse and thermokarst lakes) disproportionately affects

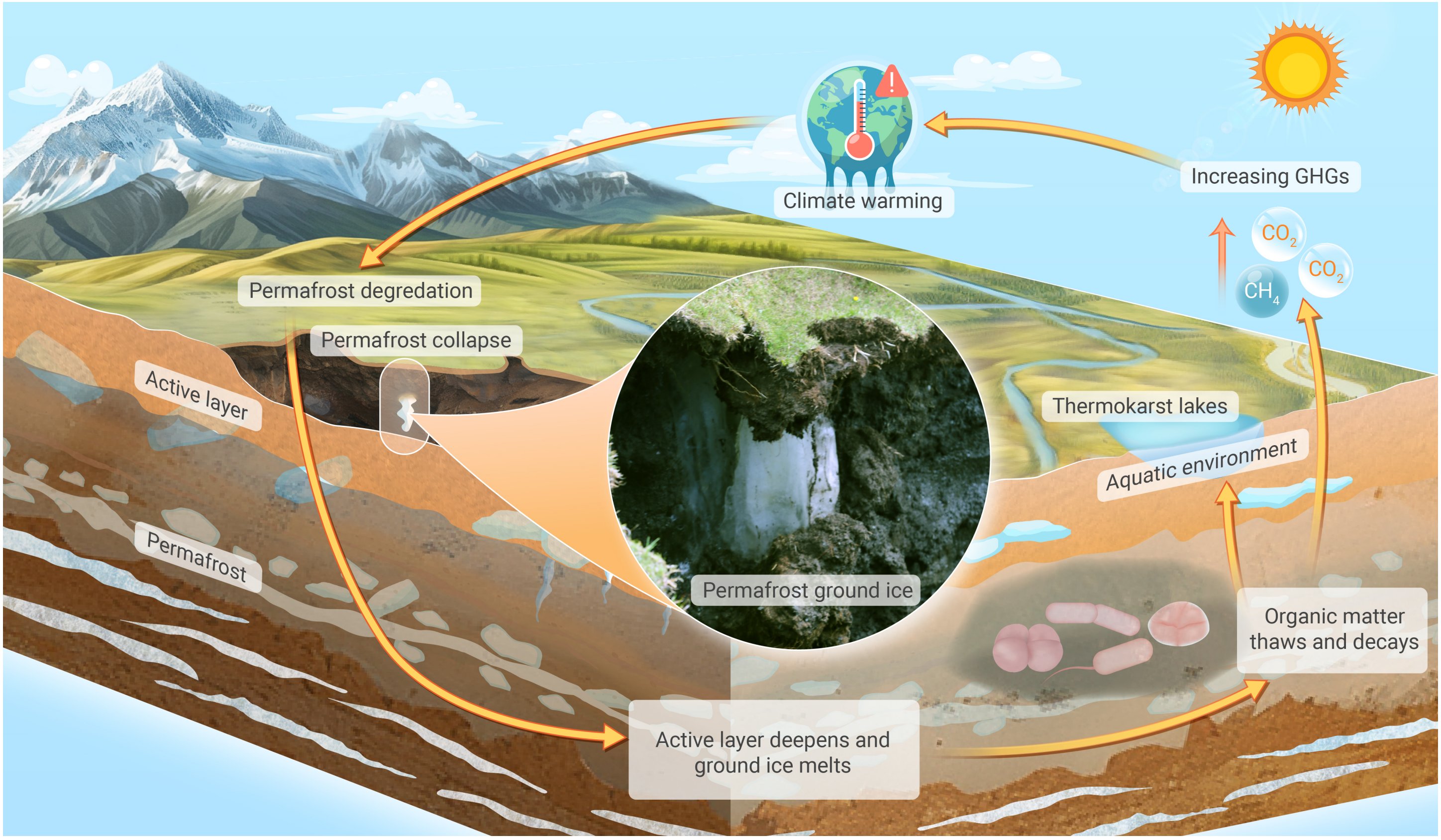

Figure 1. Sketch map of permafrost ground ice and the impact of its melting on the carbon dynamics Under climate change (particularly warming), permafrost experiences rapid degradation. The ground ice melt under ongoing warming will alter permafrost topography and subsurface water movement, further releasing stored carbon into the atmosphere and various water bodies, thereby contributing to regional climate and environmental changes.

carbon- and ice-rich areas. In particular, meltwater from rapid permafrost degradation acts as an efficient lateral transport mechanism that rapidly mobilize carbon.[5] Yet, current models overlook the role of ground ice on permafrost carbon storage, further increasing the uncertainties in assessing permafrost SOC storage. There remains a severe lack of systematic detection technology and data for regarding permafrost ground ice. Moreover, the relative importance of ground ice carbon composition, microbial properties, and substrate quality in the regulation of frozen soil carbon dynamics is not fully investigated.

Climate change impacts on permafrost and ground ice

As climate warming intensifies, thawing of ice-rich permafrost is triggering substantial geomorphic changes, such as ground surface subsidence, subsequent inundation, and hillslope failures (thermokarst landscapes). Simultaneously, the melting ground ice promotes the growth and metabolism of microbes, altering the living environment of these microorganisms and intensifying the release of greenhouse gases from thawing permafrost. Accordingly, the neglected but significant amount of frozen carbon in permafrost ground ice will be exposed, which can play a more active role in future carbon cycles. However, the amount of carbon released from ground ice and the extent of its impact on the regional climate and environment depend on many factors, such as the magnitude of climate change, rate and depth of permafrost thawing, local lithology, and hydrogeological conditions. Currently, our understanding of permafrost ground ice conditions remain poorly defined, and further modelling progress will depend largely on improvements in field knowledge of ground ice conditions and improved spatial data products. [6]

CONCLUSION AND PERSPECTIVES

The intensified climate warming in cryospheric regions has disrupted permafrost ecosystems, particularly through rapid ground ice melting. This process releases substantial amounts of permafrost carbon into the atmosphere and aquatic environments, creating a warming feedback loop that may potentially alter global carbon cycles (Figure 1). However, uncertainty remains in the estimating the volume of carbon released from ground ice and its regional climate impact. Permafrost ground ice and carbon feedback represent a complex, systematic process requiring further in-depth research to improve permafrost carbon storage estimates and provide a robust scientific and technological foundation for predicting future climate change accurately.

First, enhance permafrost ground ice observational network. Traditional methods for detecting permafrost ground ice are limited for large-scale data collection, while existing geophysical techniques often misidentify the ice beneath frozen soil, and often misjudge high resistance and high wave velocity rock and soil as ground ice, seriously hindering accurate quantification. Therefore, developing systematic data collection mechanisms of permafrost ground ice, particularly in underrepresented regions like the TP, would help bridge knowledge gaps.

Second, integrate the permafrost ground ice into climate models. Current models only simulate the response and feedback of a single element of the cryosphere to climate change at a large scale and coarse resolution. In particular, they cannot depict the synergistic effects of mutual feedbacks of carbon emissions from permafrost and ground ice. Incorporating the unique dynamics of ground ice and its carbon content into global carbon cycle models or climate models is essential for more accurate predictions of permafrost feedback loops. In addition, with continuous warming, the rapid degradation of permafrost by massive melting of ground ice (e.g., thaw slumps, rapid erosion of permafrost, and landslides), has been intensifying. However, majority of climate or earth models have not yet included the ground ice due to its spatial heterogeneity and invisibility underneath the ground.

Third, strengthen the cross-disciplinary collaboration on the permafrost ground ice. Given regional complexity and discrepancies of permafrost systems, fostering collaborations across cryosphere science, biogeochemistry, climate science and socio-economic studies will be critical to address the multifaceted challenges on the climate feedbacks of carbon source or sink by permafrost thawing and ground ice melting. In particular, permafrost and ground ice contain large amount of pollutants, which will be released associated with carbon matters under climate change. How to reveal the coupling effect of carbon and awakening pollutants on local ecosystems needs much broader research engagement.

Beyond science, permafrost thawing and ground ice melting threaten infrastructure, indigenous livelihoods, and water resources, underscoring their socio-economic and policy relevance. The monitoring and early warning system for ground ice melting should be established, which can improve the prevention and emergency response capabilities. Besides, the findings of carbon biogeochemical cycling within permafrost ground ice will align with global carbon neutrality goals or international climate agreements, which would amplify the relevance for policymakers.

The rapid thawing of permafrost and ground ice brings a series of problems such as climate, ecological, water resource risks, and disasters, which urgently require the construction of sustainable development under the rapid changes in the cryosphere. This perspective emphasizes the importance of considering permafrost ground ice to understand the mechanisms of carbon storage and emissions, providing insights for carbon sources and sinks in permafrost regions. Deeper insights into long-term permafrost-climate interactions and the subsurface conditions including ground ice will further reduce uncertainty regarding the thermal state of permafrost and its future responses.

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DECLARATION OF INTERESTS

The authors declare no competing interests.