BIOGEOCHEMISTRY

Permafrost slowly exhales methane

Permafrost soils store vast quantities of organic matter that are vulnerable to decomposition under a warming climate. Recent research finds that methane release from thawing permafrost may outpace carbon dioxide as a major contributor to global warming over the next century.

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Below the cold, wet surface of the Arctic tundra lays a vast store of organic carbon frozen in permafrost. Climate change is warming the Arctic twice as fast as any other region on Earth[1], and these permafrost soils that have remained frozen for hundreds to thousands of years are now thawing and exposing ancient organic matter to decomposition[2]. The greenhouse gases that are released from thawing permafrost have enormous potential to exacerbate climate change because permafrost stores as much carbon as is currently contained in the atmosphere[3]. Although carbon dioxide (CO_2) is emitted in high quantities and warms the climate over long timescales, methane (CH_4) has a disproportionately large warming effect over shorter timescales (<100 years). Writing in *Nature Climate Change*, Christian Knoblauch and co-authors[4] report that CH_4 production from thawed permafrost may contribute more substantially to warming than previously appreciated.

Permafrost-underlain landscapes are cold and often wet because permafrost acts as a barrier to drainage. These conditions slow microbial breakdown of plant litter and favour the accumulation of partially decomposed organic matter in soils. Organic carbon that is frozen in permafrost can be sequestered from the atmosphere for thousands of years. However, as ground temperatures increase and permafrost thaws, microbes can access the newly defrosted carbon and respire the greenhouse gases (GHGs) CO_2 and methane CH_4. The relative amounts of CO_2 and CH_4 that are produced depend largely on environmental factors, particularly soil saturation. Drier soils, where decomposer organisms use abundant oxygen to break down organic compounds, release CO_2. Both CO_2 and CH_4 are more slowly released from wet soils, where decomposition is limited by low oxygen availability.

The relative emissions of CO_2 and CH_4 under future warming scenarios, and their relative contributions to future warming, remain uncertain. The main finding of Knoblauch and co-authors is that CH_4 production from anoxic (oxygen-free) systems may account for a higher proportion of global warming potential (GWP) than previously appreciated, surpassing contributions of CO_2 (Fig. 1). To determine this, Knoblauch et al. used a long-term (seven-year) incubation experiment to measure CO_2 and CH_4 release from mineral permafrost thawed at a moderate 4 °C. Such laboratory incubations are commonly used to monitor how decomposition pathways and GHG production respond to increasing temperatures. In contrast to previous studies, these authors monitored production after stable methanogenic communities had established, which often took months to years in their incubations.

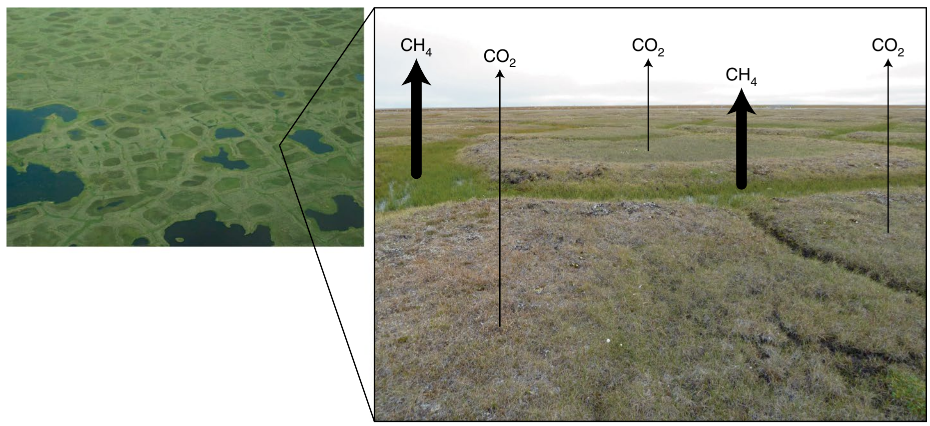

Fig. 1 | Methane release from permafrost. Left, Polygonal Arctic tundra underlain by permafrost, as viewed from a flight from Nome to Barrow on the North Slope of Alaska. Right, Permafrost that thaws in saturated areas (green vegetation) has the potential to emit CH_4 with substantial GWP. Permafrost that thaws in drier areas (tan vegetation) may emit more C as CO_2, but with less GWP. The size of the arrow is proportional to the global warming potential per molecule of each gas.Credit: Chonggang Xu, NGEE Arctic, Los Alamos National Laboratory (left); David Graham (Oak Ridge National Laboratory), modified by Elizabeth Herndon (right).

Soils warmed in the absence of oxygen produced GHGs ($CO_2 + CH_4$) with twice the GWP of soils warmed in the presence of oxygen, even though the latter lost three times as much permafrost carbon. Much of this higher GWP was due to CH_4 production. Importantly, anoxic treatments emitted equal amounts of CH_4 and CO_2, which contradicts previous studies where CO_2 was found to be the dominant GHG produced under both oxic and anoxic conditions. This discrepancy is probably explained by differences in dominant microbial populations — the incubations described by Knoblauch et al. fostered optimal conditions for methanogenesis, while other incubations were probably dominated by CO_2-producing anaerobic respiration.

Recent syntheses of similar incubation studies have reported that the GWP of thawing permafrost is dominated by CO_2 from aerobic respiration[5,6]. These studies have suggested that drier portions of the landscape are thus more important contributors to GHG production and future warming. Knoblauch et al. contend that CH_4 production in these incubations is often underestimated because methanogenic communities frozen in permafrost sometimes require years to become fully active upon thaw. Nearly all of their incubated soils had active methanogenic populations, and methanogenesis was quickly established in the remainder of soils once inoculated with active populations. Although their study was limited to a small collection of mineral permafrost soils, these results suggest that most soils have the capability to generate CH_4 under the appropriate environmental conditions. That is, methanogenesis is not constrained by substrate availability and is rarely limited by the presence of methanogens. Rather, soils only need to be thawed under saturated conditions for a suitable period to become sources of CH_4. Given the widespread occurrence of wetlands across the tundra, it is reasonable to predict that vast expanses of Arctic permafrost will thaw under saturated conditions. Indeed, by integrating results of their incubations with predictions of future thaw patterns across the entire Arctic, the authors modelled that permafrost thawed under saturated conditions will produce more CO_2-equivalents by 2100 than permafrost thawed under drier conditions.

Knoblauch and co-authors demonstrate in this study that permafrost soils have the capacity to produce substantial amounts of CH_4 in a warming Arctic. These results challenge previous assertions that CH_4 will only play a minor role in shaping future climate. However, the response of permafrost landscapes to climate change is complex, and many other factors will influence where methane is produced and whether it makes it to the atmosphere. On a broad scale, changing hydrology due to permafrost thaw will influence soil saturation, and thus the distribution and abundance of CO_2 and CH_4 production[7,8]. Transport of methane from deep soils to the atmosphere will also be controlled by freeze–thaw dynamics[9] and the activities of CH_4-oxidizing microbes and CH_4-transporting plants. However, GHG production lies at the foundation of these processes, and this research underscores the need to improve understanding of carbon cycling across different redox regimes in Arctic landscapes. ❐

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