Climate change and the permafrost carbon feedback

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Objectives:

- This paper presents an overview of new insights gained from a multi-year synthesis of data.
- One goal of the synthesis was to constrain the current understanding of the permafrost carbon feedback to climate.
- Another goal was to attempt to provide a framework for developing research initiatives in the permafrost region which target poorly understood aspects of permafrost carbon dynamics.
- Much of the research reviewed had been published after the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPPC AR5).
- The review addresses the permafrost carbon pool, carbon decomposability, projection of change, impact of abrupt permafrost thaw, subsea carbon emissions, and model-data integration.
- An updated version of the permafrost carbon feedback to climate is created from synthesized data and presented in this paper.

New Science:

- Based on the wealth of new observations, the authors propose that greenhouse gas emissions from warming permafrost are likely to occur at a magnitude similar to other historically important biospheric carbon sources (such as land use change), but at a fraction of the current fossil fuel emissions.
- The observed and projected emissions of CH_4 and CO_2 from thawing permafrost are unlikely to cause abrupt climate change in the immediate future (few years to a decade), but are likely to be felt over decades to centuries.
- These emissions are likely to make climate change happen faster than we would expect on the basis of projected emissions from human activity alone.
- The permafrost carbon pool is now thought to comprise organic carbon in the top 3 m of surface soil, carbon in deposits deeper than 3 m (including those within the yedoma region that covers parts of Siberia and Alaska) as well as carbon within permafrost that formed on land during glacial periods but that is now found on shallow submarine shelves in the Arctic.
- The new northern permafrost zone carbon inventory reports the surface permafrost carbon pool (0-3m) to be 1,035 $\pm$150 Pg carbon (mean $\pm$ 95% confidence interval).
- The yedoma region is now thought to contain between 210 $\pm$70 Pg carbon and 456 $\pm$ 45 Pg carbon, despite new observations that the deep soils are very ice-rich, with ice occupying 50-80% of the ground volume.
- New data outside the yedoma region suggests that the poorly known permafrost regions could comprise an additional deep permafrost carbon pool of 350-465 Pg.
- Subsea permafrost carbon remains largely unquantified.
- A major cause of the landscape-scale variation in decomposability across soils was linked to the carbon to nitrogen ratio of the organic matter, with higher values leading to more greenhouse gas release.
- Research on saturated soils shows anaerobic decomposition has a lower decomposition rate than aerobic, and cumulative carbon emissions are 78-85% lower; however, the release of CH_4 is higher in anaerobic decomposition and can partially offset the lower rate.

- The complex role of vegetation in modification of carbon emissions has been highlighted in recent studies. An example is the ability of sedge stems to act as a pipe to provide a pathway for CH_4 to avoid oxidation, leading to increased carbon emission rates at sedge-dominated sites.
- New long-term laboratory incubations of permafrost soils reveal that a substantial fraction can be mineralized by microbes and converted CO_2 and CH_4 on timescales of years to decades, which would contribute to near-term climate warming.
- Field observations reveal that abrupt thaw processes are common in northern landscapes; however, mechanisms that speed thawing of frozen ground and release of permafrost carbon are entirely absent from current large-scale models used to predict the rate of climate change.
- A number of ecosystem and Earth system models have incorporated a first approximation of global permafrost dynamics, and improved models specifically address processes which were missing from earlier representations, as well as plant carbon uptake and dynamics.
- Based on estimates made by independent approaches including laboratory incubations, dynamic models and expert assessment, the authors judge that 5-15% of the terrestrial permafrost carbon pool is vulnerable to release in the form of greenhouse gases during this century under the current warming trajectory, with CO_2-carbon comprising the majority of the release.

Significance:

- A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases CO_2 and CH_4 from permafrost.
- Despite increasing research attention in permafrost regions, the magnitude and timing of greenhouse gas emissions and their impact on climate change remain uncertain.
- Although never likely to overshadow emissions from fossil fuel, each additional ton of carbon released from the permafrost region to the atmosphere will incur additional costs to society.
- The Earth system models analyzed for the IPCC AR5 did not include permafrost carbon emissions. The next assessment needs to make substantive progress analyzing this climate feedback.
- Initial intercomparison of permafrost carbon models points toward several key structural features that should be implemented by models attempting to forecast permafrost emissions. These include: defining the vertical distribution of carbon in permafrost soils to account for the way atmospheric warming at the surface propagates through the soil; distinguishing CH_4 vs. CO_2 release; and description of the interactions between permafrost thaw and surface hydrology.
- A critical issue is understanding if the terrestrial landscape in the permafrost region becomes wetter or drier in a warmer world.
- New modeling formulations for describing abrupt thaw and its implication for permafrost carbon emissions are in development, and these descriptions should be taken into account.
- The sheer size of these frozen carbon pools and the rapid changes observed in the permafrost region warrant intensive and focused attention on these remote landscapes.
- Observations and modelling steps will help forecast future change; however, it is imperative to continue developing effective observation networks, including remote sensing capability, to adequately quantify real-time CO_2 and CH_4 emissions from permafrost regions.
- Such systems are not only needed to quantify and monitor potential emissions predicted here, but also to provide early warning of phenomena and surprises that we do not yet fully understand.
- This improved knowledge of the magnitude and timing of permafrost emissions based on the synthesis of existing data needs to be integrated into policy decisions about the management of carbon in a warming world.

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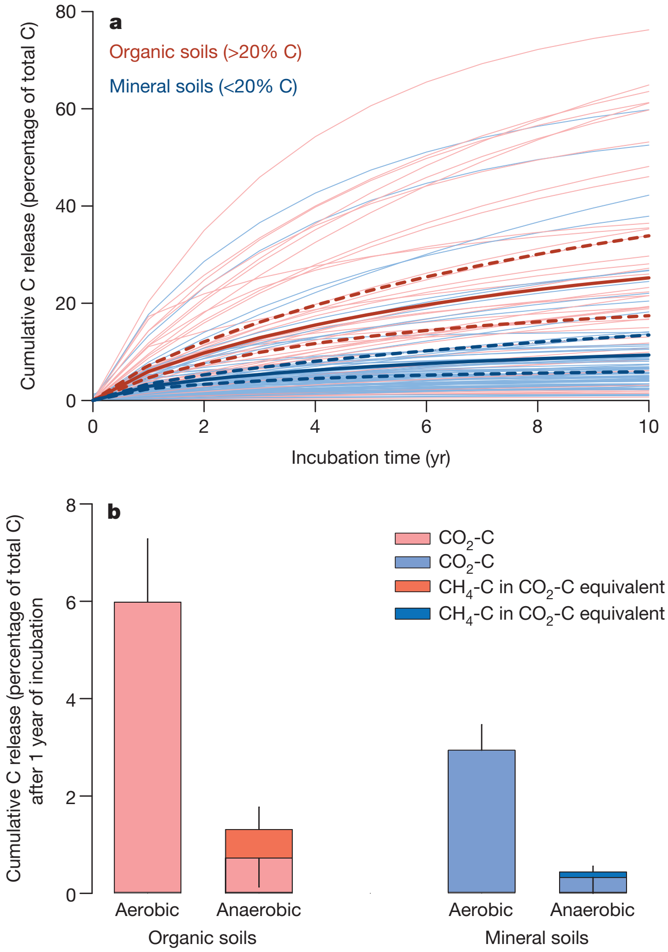
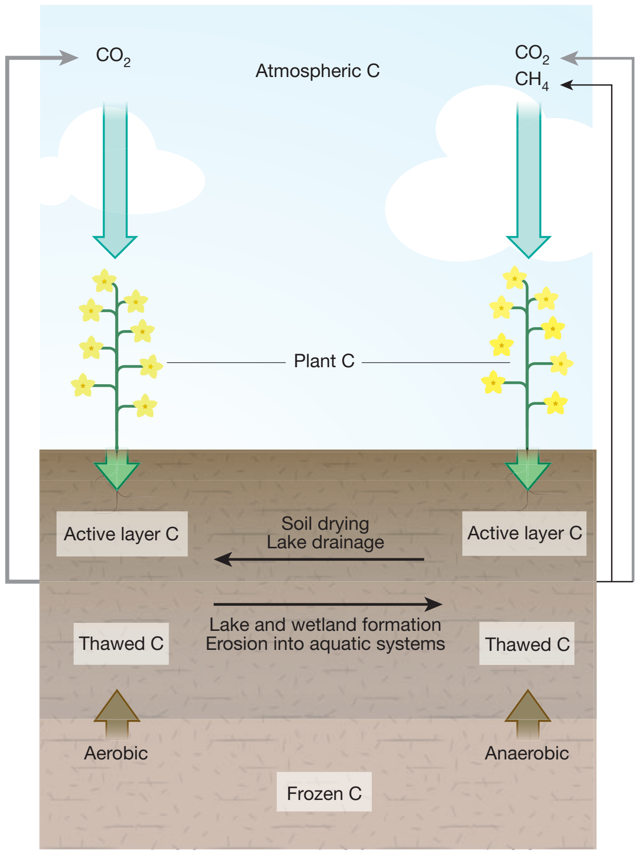


Potential cumulative carbon release. Data are given as a percentage of initial carbon. a. Cumulative carbon release after ten years of aerobic incubation at a constant temperature of 5˚C. Thick solid lines are averages for organic (red N=43) and mineral soils (blue N=78) and thin solid lines represent individual soils to show the response of individual soils. Dotted lines are the averages of the 97.5% Confidence Interval for each soil type. b. Cumulative carbon release after one year of aerobic and anaerobic incubations at 5˚C. Darker colors represent cumulative CH_4-carbon calculated at CO_2-carbon equivalent (for anaerobic soils) on a 100-year timescale. Positive error bars are upper 97.5% CI for CO_2-carbon and negative error bars are lower 97.5% CI for CH_4-carbon. N=28 for organic soils and N=25 for mineral soils in anaerobic incubations. Aerobic cumulative carbon release is calculated based on ref. 37.



Key features regulating the permafrost carbon feedback to climate from new, synthesized observations. As shown in this figure, carbon stored frozen in permafrost, once thawed, can enter ecosystems that have either predominantly aerobic (oxygen present) or predominantly anaerobic (oxygen limited) soil conditions. Across the permafrost region, there is a gradient of water saturation that ranges from mostly aerobic upland ecosystems to mostly anaerobic lowland lakes and wetlands. In aerobic soils, CO2 is released by microbial decomposition of soil organic carbon, whereas both CO2 and CH4 are released from anaerobic soils and sediments. Microbial breakdown of soil organic carbon can happen in the surface active layer, which thaws each summer and refreezes in the winter, and in the subsurface as newly thawed carbon becomes available for decomposition after it has emerged from the perennially frozen pool. The decomposability of soil organic carbon varies across the landscape depending in part on the plant inputs as well as the soil environment and also with depth in the soil profile. The landscape mosaic of water saturation is also affected by permafrost thaw. Gradual and abrupt thaw processes such as top-down thawing of permafrost (increasing the thickness of the active layer) and lake draining can expose more carbon to aerobic conditions. Alternatively, abrupt thaw processes can create wetter anaerobic conditions as the ground surface subsides, attracting local water. Carbon can also be mobilized by erosion or by leaching from upland soils into aquatic systems or sediments. Plant carbon uptake can be stored in increased plant biomass or deposited in the surface soils, which in part can offset losses from soils.