



Permafrost carbon feedbacks threaten global climate goals

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Rapid Arctic warming has intensified northern wildfires and is thawing carbon-rich permafrost. Carbon emissions from permafrost thaw and Arctic wildfires, which are not fully accounted for in global emissions budgets, will greatly reduce the amount of greenhouse gases that humans can emit to remain below 1.5 °C or 2 °C. The Paris Agreement provides ongoing opportunities to increase ambition to reduce society's greenhouse gas emissions, which will also reduce emissions from thawing permafrost. In December 2020, more than 70 countries announced more ambitious nationally determined contributions as part of their Paris Agreement commitments; however, the carbon budgets that informed these commitments were incomplete, as they do not fully account for Arctic feedbacks. There is an urgent need to incorporate the latest science on carbon emissions from permafrost thaw and northern wildfires into international consideration of how much more aggressively societal emissions must be reduced to address the global climate crisis.

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The summer of 2020 saw a record-breaking Siberian heat wave during which temperatures reached 38 °C, the highest ever recorded temperature within the Arctic Circle. During the same year, unprecedented Arctic wildfires released 35% more CO₂ than in 2019 (the previous record high for Arctic wildfire emissions since 2003), and Arctic sea ice minimum was the second lowest on record. These are clear reminders of the extreme and accelerating effects of climate change in northern regions. The Arctic has already warmed to more than 2 °C above the preindustrial level, and this rapid warming is expected to double by midcentury (1). Climate-driven changes are having transformative consequences for northern communities and ecosystems (1–3). Furthermore, because of greenhouse gas emissions from thawing permafrost and wildfire, rapid Arctic warming threatens the entire planet and complicates the already difficult challenge of limiting global warming to 1.5 °C or 2 °C.

The permafrost region contains a massive frozen store of ancient organic carbon (4), totaling approximately twice the amount of carbon as is in Earth's atmosphere. This carbon accumulated over tens of thousands of years when cold and frozen conditions protected the carbon-rich organic material (derived from dead plants and animals) from microbial decomposition. However, warming and thawing of permafrost promotes decomposition of this once frozen organic matter, threatening to turn the Arctic carbon sink into a net source of greenhouse gases to the atmosphere (5, 6). Permafrost thaw, which can proceed as a gradual, top-down process, can also be greatly exacerbated by abrupt, nonlinear thawing events that cause extensive ground collapse in areas with high ground ice (Fig. 1). These collapsed areas can expose deep permafrost, which, in turn, accelerates thaw. Extreme weather, such as the recent Siberian heat wave, can trigger catastrophic thaw events, which, ultimately, can release a disproportionate amount of permafrost carbon into the atmosphere (7). This global climate feedback is being intensified by the increasing frequency and severity of Arctic and boreal

wildfires (8, 9) that emit large amounts of carbon both directly from combustion and indirectly by accelerating permafrost thaw. Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9).

Despite the potential for a strong positive feedback from permafrost carbon on global climate, permafrost carbon emissions are not accounted for by most Earth system models (ESMs) or integrated assessment models (IAMs), including those that informed the last assessment report of the Intergovernmental Panel on Climate Change (IPCC) and the IAMs which informed the IPCC's special report on global warming of 1.5 °C (10, 11). While a modest level of permafrost carbon emissions was mentioned in these reports, these emissions were not then accounted for in the reported remaining carbon budgets. Within the subset of ESMs that do incorporate permafrost, thawing is simulated as a gradual top-down process, ignoring critical nonlinear processes such as wildfire-induced and abrupt thaw that are accelerating as a result of warming.

These nonlinear processes are particularly relevant when considering the pathway to 2 °C—that is, whether mitigation keeps global average temperature increase below 2 °C (“avoidance”) or causes an “overshoot” in temperature before stabilizing. Permafrost emissions from gradual thaw alone are highly dependent on both the extent and duration of the temperature overshoot (12). For example, for a 1.5 °C or 2 °C target, an overshoot of 0.5 °C leads to a twofold increase in permafrost emissions, and an overshoot of 1.5 °C leads to a fourfold increase (Fig. 24) (12). The impact on carbon budgets of exceeding a given temperature target will only be amplified when accounting for abrupt thaw and wildfire, both of which will have long-lasting impacts, even if global temperatures are reduced (e.g., through negative emissions) following the period of temperature overshoot.

A comprehensive understanding of the impacts of these pathways on permafrost carbon emissions—including from abrupt thaw and wildfire-induced thaw—and the implications for global emission budgets is urgently needed in order to motivate and guide mitigation decisions that will impact the state of the Arctic and the planet. Developing such an estimate is a critical next step for pinning down and communicating the relevance of permafrost carbon emissions to decision makers in order to support increased ambition to reduce fossil fuel emissions.

Scientists are aware of the risks of a rapidly warming Arctic, yet the potential magnitude of the problem is not fully recognized by policy makers or the public. Carbon emissions from thawing

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Fig. 1. Abrupt permafrost thaw on the Peel Plateau in Canada. Thawing of ice-rich permafrost can cause abrupt ground collapse, which can further accelerate thaw and amplify permafrost carbon emissions. For scale, the lake length parallel to the headwall of the thaw feature is 150 m. Image credit: Scott Zolkos (photographer).

permafrost and intensifying wildfire regimes present a major challenge to meeting the Paris Agreement’s already difficult goal of holding the global average temperature increase to well below 2 °C above preindustrial levels—and an even bigger challenge to meet the aspirational goal of limiting the temperature increase to 1.5 °C. There is an urgent need for an accelerated scientific effort to more accurately estimate and communicate the likely magnitude of increased carbon dioxide and methane emissions from a warming Arctic to better inform decisions about the “increased ambition” that is needed to keep the global temperature increase well below 2 °C. At present, not even the current scientific understanding of future emissions from a warming Arctic is reflected in most climate policy dialogue and planning. That should be remediated without delay.

Recent estimates of carbon emissions from gradual permafrost thaw alone range from ~6 Pg to 118 Pg of C (22 Gt to 432 Gt of CO₂) by 2100 if society’s global carbon emissions are greatly

reduced (12, 13), and up to about 150 Pg of C (550 Gt of CO₂) assuming weak climate policies (6, 12, 14). These emissions projections are likely an underestimate, because they do not account for abrupt thaw and wildfire. For example, under a moderate emission scenario (A1B), carbon emissions from soil and permafrost may increase by 30% by the end of the century when accounting for wildfire compared to emissions from warming alone (9), and abrupt thawing events may increase carbon emissions by 40% if current fossil fuel emissions are not reduced (7).

Without accounting for permafrost emissions, the remaining carbon budget [counting emissions through 2020 (15)] for a likely chance (>66%) of remaining below 2 °C has been estimated at ~340 Gt to 1,000 Gt of CO₂ equivalent (CO₂-e) (10) and at ~290 Gt to 440 Gt of CO₂-e for 1.5 °C (11). It is important to recognize that the IPCC mitigation pathways that limit warming to 1.5 °C without overshoot require widespread and rapid implementation of carbon dioxide removal technologies, which currently do not exist at scale (11). Within this context and considering carbon emissions from permafrost thaw—even without the additional allowance for abrupt thaw and wildfire contributions—limiting warming to 1.5 °C without overshoot is likely unattainable. Assuming we are on an overshoot pathway, permafrost carbon will increase the negative emissions required to bring global climate back down to the temperature targets following a period of overshoot (Fig. 2B). Inclusion of abrupt thaw and nonlinear processes that accelerate permafrost carbon emissions will only make the impact on society’s carbon budget worse. Recognizing the likely inevitability of overshooting the 1.5 °C target, there is an urgent need to quantify and account for the compounding impact of overshoot magnitude and duration on climate feedbacks, such as permafrost thaw.

In the face of these challenges, the Paris Agreement’s provisions and their updating at the continuing meetings of the Conference of the Parties provide the best available opportunities for embedding evolving understanding of carbon emissions from the Arctic into global decision-making. At the end of 2020, countries that signed on to the Paris Agreement were expected to renew and strengthen their nationally determined contributions (NDCs)—the pledged national contributions to the Paris Agreement goals. Subsequent rounds of increased ambition are slated to occur every 5 y. After the Climate Ambition Summit in December 2020, strengthened commitments covering 71 countries had been announced (all European Union

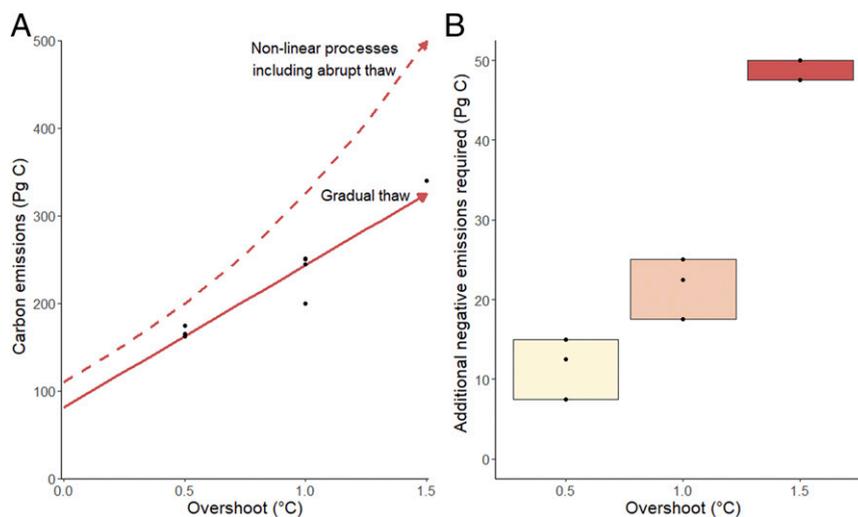


Fig. 2. Carbon emissions from Arctic permafrost thaw and the impact on global carbon budgets for 2 °C. (A) Cumulative carbon emissions from gradual permafrost thaw (solid line) and abrupt thaw, fire-induced thaw, and other nonlinear processes (dashed line) are expected to increase as temperatures “overshoot” the 2 °C temperature goal. (B) Permafrost emissions (only gradual thaw shown here) will therefore require additional negative emissions to draw temperatures back down to 2 °C. Figure combines modeled data (12) (black points), estimated trend based on these data (red solid line), and conceptual trend added for illustrative purposes (red dashed line).

[EU] member states were included in the EU's commitment). In early 2021, the United States rejoined the Paris Agreement, President Joseph Biden set a target of net-zero emissions by midcentury, and countries representing around 65% of global emissions made commitments to reach carbon neutrality. In 2023, collective progress toward the global temperature goals will be assessed through a "global stocktake."

In the context of these major milestones in climate policy, it is critical for policy makers and the public to understand how emissions from a warming Arctic affect the urgency around strengthening the NDCs to ensure that NDC goals are sufficiently ambitious. It is of equal importance that Arctic scientists and those who fund their work appreciate the need for reducing the uncertainties that observational and modeling gaps create in understanding the current and future state of Arctic carbon feedbacks. For example, despite the widespread occurrence and considerable carbon consequences of abrupt thaw, a first estimate of regional emissions from this process was completed just last year and was derived from sparse existing observational data (7). Further, there are no process-based global models that incorporate abrupt thaw, combustion of soil organic matter, or the impacts of fire on permafrost vulnerability, the latter two of which are major drivers of net carbon emissions from Arctic wildfires. Similarly, effective dissemination of this information requires that the scientific community responds to the emerging

need for integration of scientific understanding within policy-relevant frameworks. This includes increased scientific focus on understanding the impacts of 1.5 °C versus 2 °C, or even greater, warming; the changing feasibility of these temperature targets; the implications of following an "overshoot" rather than "avoidance" pathway; and the impacts of the magnitude and duration of the temperature overshoot.

While more observational data and model improvements are needed, these scientific advances alone will not lead to appropriate action without coordinated and intentional communication between scientific and policy communities. Effective integration of science with policy—in this domain as in others—requires dialogue rather than a one-directional transfer of scientific information. This dialogue is needed both to support policy communities in adequately considering and responding to the rapidly developing body of scientific knowledge and to convey challenging concepts, such as those associated with both high risk and high levels of uncertainty. A strategic commitment to engaging with relevant audiences requires time and resources but, in return, will result in more effective transfer of knowledge and, ultimately, more effective climate change policies that are urgently needed to address the global climate crisis.

Data Availability. There are no data underlying this work.

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