CASCADE INSTITUTE

BRIEF

Entangled climate risks:

Interactions between permafrost thaw and wildfires

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ABSTRACT

The literature on wildfires and their effect on permafrost thaw and permafrost carbon feedback in a time of accelerating climate change reveals that these interconnected climate risks are intensifying, and yet their interconnections remain poorly understood. These interactions—which threaten to push the global climate system into a dangerous feedback loop—are underrepresented or missing entirely from many Earth system models, leaving international leaders to make policy based on inaccurate greenhouse gas emission calculations and carbon budgets. These gaps in knowledge and understanding suggest an urgent need for better information, including the standardization of sampling and observation protocols, better models, and better data to inform those models.

In addition to uncovering a general need for more collaboration among researchers and policymakers, this survey of the latest permafrost and wildfire research further reveals a clear scientific consensus that, even without a comprehensive understanding of the growing risk of fire on permafrost thaw and permafrost carbon feedback as the climate warms, the dangers are clear enough to indicate that mitigative action—targeting not only global emissions but also permafrost thaw and wildfires more directly—is urgent and necessary.

1. INTRODUCTION

Rising global temperatures cause a variety of environmental changes, many of which affect and exacerbate one another. This report focuses on two such changes: permafrost thaw and increased wildfire activity. In most scientific publications, permafrost and wildfires are considered separately (Treharne et al., 2022). Even when mentioned together, there has been limited examination of their interaction (Abbott et al., 2022; Janssen et al., 2023; Schädel et al., 2024). Far from receiving attention commensurate with their influence in the climate change puzzle, they are usually mentioned as gaps in the literature requiring greater attention.

This report thus assesses the literature on wildfire and permafrost thaw, highlighting research that spans both issues (Figure 1). We want to know:

1. How does wildfire affect permafrost thaw; and how does permafrost thaw affect wildfire?
2. How are both connected to the permafrost carbon feedback?
3. What do researchers and policymakers need to do to fill knowledge gaps and address the pernicious interactions between permafrost thaw and wildfires?

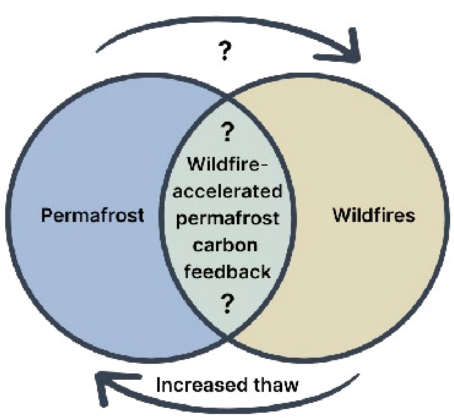


Figure 1: The reciprocal impact of permafrost thaw and wildfires, highlighting question #1 and #2 above.

Permafrost carbon feedback

Around 14 million square kilometres in the northern high latitudes—a vast area roughly 50 per cent larger than the land mass of Canada—are underlain by permafrost, which is defined as ground that has remained frozen, winter and summer, for more than two years (Obu, 2021) (Box 1). This permafrost stores as much as 1.6 trillion metric tonnes of carbon, equal to twice the amount of carbon contained in the atmosphere and more than three times the carbon in all the forests on Earth (Hugelius et al., 2014). With the Arctic warming at up to four times the global average (Rantanen et al., 2022), rising atmospheric temperatures are promoting thaw, allowing upper layers of soil to decompose and release greenhouse gases (carbon dioxide and methane), which further accelerates atmospheric warming.

Box 1: Permafrost and permafrost thaw

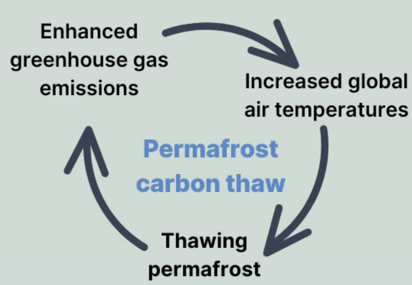
Permafrost is ground that stays frozen (below zero degrees Celsius) for two or more consecutive years. Above the permafrost, an active layer of varying thickness generally thaws every summer, supporting a shrubby vegetative cover that isolates and insulates the underlying frozen ground. Permafrost occurs in different concentrations—sporadic (10-50 per cent), discontinuous (50-90 per cent), and continuous (greater than 90 per cent)—and permafrost thaw happens either gradually or abruptly.

The positive feedback loop—permafrost thawing, releasing carbon dioxide and methane which promotes further thaw—is called the *permafrost carbon feedback* loop, (Box 2). The exact impacts of permafrost carbon feedback on the global climate are still poorly understood (Schuur et al., 2022).

While most permafrost thaw research has focused on localized issues, such as subsidence, infrastructure damage, and coastal erosion, an increasing number of researchers are now trying to quantify the impact of thaw-related greenhouse gas emissions. Early mentions of permafrost carbon feedback gave lower estimates of its impact (Koven et al., 2011; Schuur et al., 2015), but recent publications on wildfires and permafrost thaw warn of increased permafrost carbon feedback effects (MacDougall, 2021) and suggest that abrupt thaw could double the radiative impact of the released gases. But global estimates of the increase in carbon emissions from wildfire and permafrost interactions are only beginning to emerge (see, for example, Treharne et al., 2024).

Box 2: Climate feedback loops

In a positive, or self-reinforcing, feedback loop, a change in an initial condition (the cause) creates a similar change in the effect, which then intensifies the change in the cause, which then intensifies the change in the effect, and so on. With the permafrost carbon thaw, greenhouse gases warm the atmosphere causing permafrost to thaw, releasing more greenhouse gases that increase and accelerate warming.



The effect of permafrost thaw and wildfires on global carbon budgets

Permafrost thaw, abrupt or gradual, leads to significant release of heat-trapping gases, as well as various landscape changes, including pond and lake formation, that affect the amount and type of emissions—carbon dioxide or methane—which have different warming potentials (in other words, they warm the atmosphere to different degrees on different timescales, with methane trapping much more heat than carbon dioxide, but degrading much faster). This, in turn, can have a massive impact on the calculations on which international bodies are building carbon budgets—estimates of how much carbon can still be added by humans to the atmosphere before pushing the world over a dangerous threshold. Yet, few Earth system models represent permafrost carbon (MacDougall, 2021; Schädel et al., 2024). MacDougall found only two of 18 models accounted for permafrost carbon feedback.[1] The few models that include permafrost thaw only include gradual thaw (Walter Anthony et al., 2018; Turetsky et al., 2019, 2020), even though abrupt thaw, abetted by wildfire, could as much as double related emissions (Turetsky et al., 2020).

Even studies that include permafrost do not cover deep permafrost, such as Yedoma in Siberia, and the permafrost beneath Alaska (late-Pleistocene permafrost, formed during previous ice ages), or subsea permafrost. They also register methane in a fixed percentage, even though its fraction is likely to be increasing (Gasser et al., 2018).

Wildfires and climate change

Many studies mention that wildfire, a major cause of abrupt permafrost thaw, is an important factor when projecting cumulative thaw and permafrost carbon feedback (Gibson et al., 2018). Fires above permafrost are likely to cause widespread vegetation change and/or irreversible permafrost thaw

[1] Among the few Earth system models that include permafrost impacts, the OSCAR model includes modules developed for carbon degradation and emission in high latitudes, generating emission estimates that fall in the same range as other models, but that include large uncertainties (Gasser et al., 2018) Gasser et al. (2018) compared different emission scenarios for different time steps (2100, 2200, 2300) between OSCAR results and previous studies, and found that including the permafrost component reduces exceedance budgets by a few per cent: 30 and 60 $GtCO_2$ for 1.5°C and 2°C, respectively.

(Jafarov et al., 2013; Talucci et al., 2022). Gibson et al., (2018) state, "Permafrost vulnerability to climate change may be underestimated unless effects of wildfire are considered."

The incidence of wildfire is decreasing globally, due to a reduction of tropical savannah and grassland fires (Hanes et al., 2019; Janssen et al., 2023). But the increasing number and intensity of extratropical fires (especially boreal) may offset the greenhouse gas emission decrease in the tropics (Cunningham et al., 2024; Li et al., 2024; Potapov et al., 2017). Fires can be caused by humans (e.g., accidentally or for agricultural purposes) or by lightning. While human-induced fires are decreasing, lightning fires are increasing in number, frequency, duration, and burned area, especially in western Canada (Chen et al., 2021; Hanes et al., 2019).

Around 91 percent of extratropical forests in the Northern Hemisphere occur in permafrost areas (Janssen et al., 2023). Researchers have reported for more than a decade that Arctic lands are losing their strength as a sink for carbon dioxide (McGuire et al., 2010), a change that wildfire exacerbates. Thus, it is important to understand and quantify the climatic effects of wildfire in permafrost regions, and to assess the effects and potential increase of extreme fire events (Byrne et al., 2024; Talucci et al., 2022).

2. INTERACTIONS BETWEEN WILDFIRES AND PERMAFROST THAW

The effect of wildfires on permafrost thaw

Identifying the interplay of permafrost thaw and wildfire is essential to quantifying permafrost carbon feedback, a crucial parameter when creating the carbon budgets that inform policy for addressing the global climate crisis (Natali et al., 2021).

Wildfires affect permafrost directly and indirectly, both immediately and over the longer term. Acting directly, wildfires can trigger abrupt thaw, which is often irreversible. Indirectly, wildfire can strip or reduce vegetative cover (Treharne et al., 2022), change hydrological and carbon cycle features that can increase the active layer thickness (Treharne et al., 2024), and change vegetative content, such as by turning forests into shrublands (Talucci et al., 2022). Fires also affect soil composition and general climate conditions, including decadal climate trends (snow cover, etc.) (Brown et al., 2015).

Wildfire impact is area-specific, depending on the nature of existing vegetation, soil, and permafrost, as well as fire severity and terrain (i.e., poor vs. well-drained). A permanently frozen underlayer resists drainage, keeping the summertime surface layer wet, creating anoxia and natural fire protection (Koven et al., 2015). As the ground warms, drains, and dries, carbon-dense peatlands, nearly half of them located above 60°N, are especially vulnerable, and they recover more slowly than boreal forest after a fire (Witze, 2020).

The effect of permafrost thaw and permafrost carbon feedback on wildfires

Permafrost thaw and related climate feedbacks have a reciprocal impact on wildfire. As thaw affects vegetation cover and hydrology, it can promote dryer conditions that raise the risk of wildfire (Abbott et al., 2022; Holloway et al., 2020). The 2022 *IPCC Special Report on Ocean and Cryosphere Changes* warned that thawing permafrost and a decrease in snow cover affect Arctic hydrology, increasing wildfire frequency and instances of abrupt thaw (SROCC, 2022).[2]

Rising global temperatures lead to more frequent and intense storms, including a higher frequency of lightning, triggering more

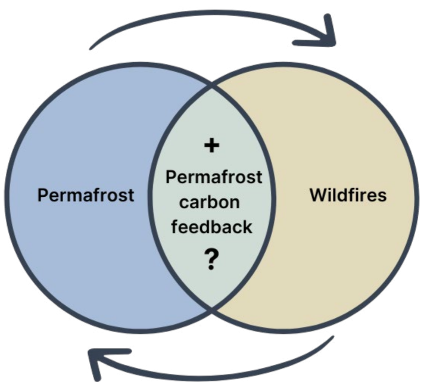
[2]Permafrost thaw can sometimes result in wetter conditions through subsidence and thermokarst (Foster et al., 2022).

fires in boreal forest and tundra (Chen et al., 2021; Janssen et al., 2023; Veraverbeke et al., 2017). Decreased precipitation (drought), increased temperature, increased fire season length, and earlier snowmelt also amplify the number and impact of wildfires (Talucci et al., 2022).[3]

There is also a lightning-fire feedback: a warmer atmosphere induces more lightning strikes, setting more fires that liberate more carbon from burned vegetation (See Figure 2; Chen et al., 2021; Janssen et al., 2023).

Figure 2

Thaw-induced hydrological changes and decomposition-induced vegetation changes favour conditions for fire.



Increased thaw through active layer deepening, vegetation change/loss (insolation loss), and carbon cycle changes (increased decomposition).

3. THE CHALLENGES

Capturing the complexity of permafrost thaw and wildfires in climate models

> *"Incorporation of permafrost carbon feedbacks into [Earth system models] is of unique urgency given the exceptional warming in the Arctic and the threat to global climate mitigation goals." (Schädel et al., 2024)*

Climate models urgently need more and better data to represent permafrost thaw and other processes that push Earth's climate system toward tipping points (Gasser et al., 2018). Key data gaps include the impacts of permafrost thaw (especially abrupt thaw) on carbon emissions, local-scale susceptibility to "fire-permafrost thaw feedback," and large-scale mapping of abrupt permafrost thaw features. Calls to include carbon feedback in Earth system models emerged as early as 2010 (McGuire et al., 2010; Vonk et al., 2015). And Abbott et al. (2016) recommend integrating three variables—water balance, vegetation distribution, and permafrost degradation—to improve model accuracy and validate permafrost carbon feedback projections.

Earth system and climate models necessarily mirror complex natural systems. Yet, the complexity of climate models often results in parameters being held out of calculations; for example, Koven et al., (2015) included methane production, but excluded fire and other ecological and morphological processes. Some models overlook the effect of wildfires, or even the release of methane, relying solely on calculations of carbon dioxide emissions (MacDougall et al., 2012, 2015), while all models overlook abrupt permafrost thaw.

Wildfire is often mentioned as a major driver of abrupt permafrost thaw and an influence on permafrost carbon feedback (Schädel et al., 2024). Conditions (wet versus dry) are also important as they favour the emission of either carbon dioxide or methane. Yet, fire-driven soil decomposition and vegetation changes are generally missing in Earth system models (Abbott et al., 2016). Even the Earth system models that represent wildfires do not represent the burning of soil organic matter, particularly peat.

Communication

Uncertainty makes it difficult to communicate climate outcomes and policy choices clearly

[3] Most mainstream climate change assessments predict more future precipitation in high latitudes, but this increase is offset by "evaporative demand" from higher temperatures that can result in more droughts.

and credibly, in part because Earth system models without permafrost carbon feedback data are unlikely to deliver a reliable number for the global carbon budget (Gasser et al., 2018).

In both popular media and scientific literature, permafrost carbon feedback often gets communicated in extremes—from a "ticking time bomb" to the "we-still-have-time" scenario—while the truth is likely somewhere in between (Abbott et al., 2016). Regardless of the confusion, Abbot says, "Arctic and boreal biomass should not be counted on to offset permafrost carbon release and [...] that the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario."

As it is now clear that wildfire, permafrost thaw, and permafrost carbon feedback have impacts far beyond the Arctic, the literature shows a consensus that, in addition to increasing research on mitigation strategies to protect permafrost grounds or slow the rate of permafrost thaw, the pressing challenge is to communicate the urgency of reducing emissions and making wise energy choices, actions that have the best chance of mitigating permafrost changes and permafrost carbon feedback (Abbott et al., 2022).

4. RESEARCH PRIORITIES

Given insufficient understanding of the impacts of wildfire on permafrost thaw, and of the combined effects of fire and thaw on climate change, the following are the most urgent research priorities:

Earth system models: Permafrost processes, including those caused by wildfires, must be integrated into Earth system models. These models should also include causes and drivers of fire, to improve forecasting of fire frequencies and development.

"Wildfire, thawing permafrost, and permafrost carbon feedback in the North are combining to raise the global temperature—perhaps catastrophically."

Immediate and enduring effects of fire on permafrost thaw: Wildfire and permafrost thaw need to be studied in combination (and their interactions included in Earth system models). Hydrological processes connected to wildfire and permafrost thaw also need to be considered together. This research should be collaborative and interdisciplinary, connecting disciplines (fire and permafrost science, observations, field measurements, and modelling) and bridging the gap between scientists and policymakers.

Other research priorities include:

- changes in fire regimes in the Arctic and subarctic,
- large-scale remote sensing-based maps of abrupt permafrost thaw features and their relation to wildfire events,
- increased monitoring in the Arctic (for example, carbon flux near areas of wildfire-permafrost interactions, lightning, and wildfire occurrences), and
- collaborative and interdisciplinary research on the impacts of wildfire on permafrost thaw and permafrost carbon feedback among disciplines (particularly between fire and permafrost science) and between scientists and policymakers.

5. RECOMMENDATIONS

Reviewing the literature and conferring with leading scientists have clarified the state of knowledge about the interaction of wildfire with permafrost thaw and permafrost carbon feedback. This review has also identified critical uncertainties that are undermining the accuracy of the carbon models and budgets on which the international community is basing crucial climate policy.

The uncertainties are plentiful: There are immediate needs for research of hydrological carbon fluxes, permafrost thaw processes, fire regime shifts, and more (Abbott et al., 2016; Schädel et al., 2024; Turetsky et al., 2020). But the risks are also clear: Carbon losses through wildfire could increase fourfold by the end of the century (Abbott et al., 2016), leading to a 30 per cent increase in greenhouse gas emissions from the permafrost carbon feedback (Natali et al., 2021). Wildfire, thawing permafrost, and permafrost carbon feedback in the North have an increasing capacity to raise the temperature—potentially catastrophically—in the whole world.

Accordingly, there is an urgent need for increased research funding in order to:

- increase collaboration among permafrost and fire researchers, and policy makers;
- improve the state of data on wildfire, permafrost thaw, and permafrost carbon feedback (including high-resolution coverage and temporal/spatial scales;
- incorporate abrupt permafrost thaw, related hydrological processes and combustion of soil organic matter into Earth system models;
- standardize sampling and observation protocols to assure data comparability;
- conduct research on the differing effects of wildfire-driven carbon dioxide and methane emissions on abrupt permafrost thaw (SROCC, 2022);
- encourage the IPCC to focus more on the interactions between permafrost thaw, permafrost carbon feedback, and wildfires; and
- protect permafrost, primarily by reducing fossil fuel emissions (Abbott et al., 2022), but also by exploring mitigation strategies that directly target permafrost thaw and wildfires.

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