Assessing the extent of greenhouse gas emission via permafrost melting

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1 Abstract

As the Arctic region continues to warm, permafrost melting contributes greenhouse gases to the atmosphere by microbial digestion of soil organic carbon (SOC). While the permafrost-methane feedback is generally considered to be a serious contributor to future warming, there are many sources of uncertainty on the mechanisms of the feedback effect. Although some models suggest that new biomass growth could offset carbon emissions from permafrost thaw, it is possible that water stress and wildfire could render the Northern high latitudes an even less hospitable landscape for vegetation (Abbott *et al* 2016). In addition, most models accounting only for gradual thaw emissions are likely underestimating the contribution of abrupt thaw events, in the form of landslides, thermokarst lakes, and ground collapse (Turetsky *et al* 2020). Another source of uncertainty is the timescale of thaw emissions: as permafrost melts, SOC digestion gradually accelerates over time, reflecting observations that post-permafrost soil emits more greenhouse gases if it thawed a longer time ago (Martinelli 2020). Thus, we may expect a lag period of several decades/centuries between the melting of permafrost soil and the most concentrated emissions into the atmosphere. Despite all of these proposed mechanisms, however, ice core records dating back to the last major deglaciation event suggest only a minor mobilization of buried organic carbon. These findings, presented by Dionysius *et al* (2020), suggest that the feedback occurs on a much smaller scale than is currently expected. This term paper analyzes the extent of the emissions problem faced and the threat posed by the feedback mechanism, considering a variety of viewpoints from recent literature.

2 Introduction

The circumpolar permafrost region, like other areas at high latitude, is experiencing rapid change due to global warming with polar amplification. While the sea-ice albedo feedback and other mechanisms speed up Arctic warming, it has become a concern that the permafrost-methane feedback may soon cause a dramatic shift in radiative forcing, causing catastrophic heating in the Northern latitudes. The permafrost carbon pool is massive, estimated to contain 1672 Pg of SOC, roughly double the atmosphere's total carbon content (Martinelli). Significant, alarming emissions have already been observed, and have prompted extensive study of the greenhouse gas fluxes in the region. Meanwhile, landscape destabilization is observed as a result of permafrost thawing, flooding groundwater capacity and inducing landslides, sinkholes, and wetland expansion in the form of thermokarst lakes, which release methane directly through the water column. The rate of change in polar regions has led to intense scrutiny and future projections, some of which must be significantly reworked in order to accurately reflect warming patterns.

3 Background

3.1 Methane-permafrost feedback

In most areas of the globe, detritus is digested relatively quickly by insects and microorganisms, especially in warm, active ecosystems. In the polar regions, where some areas experience year-round temperatures close to or below freezing point, the decay process lasts significantly longer, allowing biomass to deposit into the soil where it becomes frozen as a long term carbon reservoir. Since permafrost is perennially frozen, very little decomposition occurs until a warming event forces the soil to thaw. Warmer temperatures expand the range of methanogenic bacteria to the thawed soil, beginning the decay of stored carbon into methane and carbon dioxide by microbial respiration. These greenhouse gases enhance atmospheric warming, which further contributes to permafrost thaw, sustaining the positive cycle.

3.2 Carbon-14 dating

^{14}C is a carbon isotope that experiences radioactive decay, making it a useful measurement of age for deposited carbon in ice cores. Carbon-based life forms with a roughly uniform isotope ratio; after the biomass is deposited into soil and frozen, the ^{14}C will decay as the rest remains inert. Once this matter is digested, the methane released will be absorbed by the ice, preserving the isotope ratio, although it continues to decrease as a trapped gas bubble. ^{14}C dating of an ice sample thus accounts for all the time that has passed since formation of the original biomass, including both its time kept in permafrost and in the ice core as a trapped gas. For ice core records spanning back long timescales (longer than its radioactive half life of 5730 years), it is difficult to detect the isotope presence, and therefore huge volumes of ice must be collected to retrieve accurate data (Dionysius *et al*). By dating the ice itself using other methods, researchers can identify a difference between the ice formation and the carbon content within the ice, indicating whether or not the stored carbon (mainly methane and CO_2) is derived from the permafrost reservoir or contemporary sources such as bacterial digestion in surface wetlands.

4 Body

4.1 Sources of uncertainty in the methane-permafrost feedback

4.1.1 Future biomass response to warming

Warming in the circumpolar permafrost region is a complex process with numerous ecosystem responses that cloud future predictions of carbon flux. One of these responses is the abundance of the vegetation community: some models predict warming to aid plant growth across the region, potentially offsetting the emissions of permafrost soil. In a survey of permafrost-region researchers, Abbott *et al* found that expert opinion predicts a marginal increase, or possible decrease, of circumpolar biomass. The boreal region is expected to experience the most significant changes, while tundra biomass will likely remain a small source of variability until 2300 (Abbott *et al*). Meanwhile, the survey suggested a nearly unanimous prediction of wildfire emissions increase, and a highly likely increase in hydrologic carbon flux, the transport of dissolved and particulate carbon into regional oceans and freshwater. Thus the study concludes that the permafrost regions will almost certainly become a net carbon source by 2100 even with very little human development.

4.1.2 Impact of abrupt thaw emissions to total regional carbon flux

Another potentially underestimated carbon source is the production of methane from abrupt thaw. As explained in section 4.2, methane released from deep permafrost and sub-sea hydrates have the potential to be mostly oxidized or converted to CO_2 before reaching open atmosphere (Dean *et al*). Meanwhile, a key characteristic of abrupt thaw is the exposure of permafrost to the open air, or a very short water/soil column. Abrupt thaw is initiated by soil collapse due to melting, resulting in sinkholes, rapid erosion on hillsides, thermokarst lakes, and any feature exposing permafrost. In Turetsky *et al*, a model was used to predict abrupt thaw emissions at about 80 ± 19 PgC by 2300, representing 40% as much emission as a multi-model gradual thaw mean of 208 PgC. Since abrupt thaw events are localized geographically to very small sites, they are only expected to occur on about 20% of permafrost landmass, but potentially contribute up to half of the region's emissions (Turetsky *et al*). This concentration makes modeling abrupt thaw sites inaccurate and unpredictable, adding further uncertainty to the feedback, and suggesting model underestimation of carbon flux.

4.1.3 Time horizons of emission from post-permafrost soil

Following an experimental approach, Martinelli (2020) demonstrates the carbon flux of post-permafrost soils subjected to different conditions. Soil samples were collected from three sites and incubated for 121 days under two temperature profiles (5 and 15°C) each with one sample in an aerobic environment and the other anaerobic. The soil from the longest-thawed site had the highest GHG emission (Martinelli) when compared with the same treatments for the other sites. As expected, higher temperature, aerobic conditions allow for the most microbial decomposition. However, further testing is needed to assess various realistic conditions, possibly mirroring annual mean temperatures and solar flux in permafrost regions. In addition, the study was not designed to account for deep permafrost, where soil and marine bacterial communities above the permafrost could interact with the emitted gases. However, regardless of the quantity of GHGs entering the atmosphere, the experiment results suggest that the emissions that do occur will increase significantly over time and accelerate as a function of warming, inducing a time lag that may intensify the effects of permafrost thaw as a result of melting that is already occurring today.

4.2 Evidence suggesting lack of feedback during the last deglaciation

While permafrost is modeled and expected to produce significant carbon flux in the 21st century and onward, past records from the last deglaciation suggest a relatively minor contribution from permafrost methane, the key compound expected to destabilize climate in the future. While the last major warming event occurred on a slower natural timescale, its pattern (featuring a polar amplification) and scale were similar to current and projected conditions, allowing its use as a proxy for future warming. Dionysius *et al* (2020) found that collected ice core records, dating back from 15 to 8 thousand years before present, illustrate a stronger effect from contemporary methane sources rather than old carbon stores within the permafrost soil. The atmospheric carbon in this timeframe was measured by isotope ratios within the ice, as explained in section 3.2. The results of the study surprisingly indicate a permafrost methane release of only 19 Tg per year or less, smaller than emissions from biomass burning or microbial wetland decay. It is difficult to tell whether permafrost methane will follow a similar pattern for human-induced warming; however, Dean (2020, published concurrently) provides an explanation for a lack of methane emission, citing oxidation to carbon dioxide before atmospheric entry. When methane is emitted from deep permafrost or submarine methane hydrates (another significant carbon pool sensitive to heating), it must travel through a long column of microbial communities present in the soil or seawater. These microbes can typically oxidize the vast majority of methane into carbon dioxide, not mitigating the climate feedback completely, but erasing the presence of methane. This process could likely be tested in a laboratory setting, providing an opportunity for significant modeling adjustments when coupled with active layer and ocean profiles. The oxidation capacity of the surface layers in the circumpolar regions is essential to developing a robust relationship between warming and permafrost emissions.

5 Conclusions

The circumpolar permafrost region is a rapidly changing environment, as well as a highly active area of research. The methane-permafrost feedback has been projected as a huge source of variability in future climate change, with the potential to cause runaway warming in the polar regions. There are numerous uncertainties, including biomass accumulation (Abbott *et al*) as well as the extent of abrupt thaw sites (Turetsky *et al*). However, current publications also suggest that the feedback is not necessarily an immediately damaging process, and perhaps not even a process that will be of concern if human emissions can be mitigated in a reasonable timeframe. Soils exhibit much higher activity long after the permafrost thaws (Martinelli), but even high activity beneath an active layer or a water column may only result in carbon dioxide emissions (Dean). The strongest evidence lies with assessments of ice core records showcasing a low atmospheric content of old methane (Dionysius *et al*). Nonetheless, warming in the circumpolar region is still amplified by other effects, among them the sea-ice albedo feedback and an increase in biomass burning and hydrologic carbon flux, although a partial offset by vegetation growth is possible. Even if the potential permafrost methane feedback is proven to be insignificant, these findings should not influence public policy or distract from mitigating emissions. They should, however, be studied further and incorporated into models to better forecast warming in the circumpolar regions.

6 References

- Abbott, B.W. *et al.* "Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment." *IOP Science,* Environmental Research Letters, vol. 11, no. 3, 7 March 2016, pp. 3, 7.
- Dean, J.F. "Old methane and modern climate change." *Science,* vol. 367, issue 6480, 21 February 2020, pp. 847.
- Dionysius, M.N. *et al.* "Old carbon reservoirs were not important in the deglacial methane budget." *Science,* vol. 367, iss. 6480, 21 February 2020, pp. 907.
- Martinelli, Johan. "Greenhouse gas flux over a 50-year post permafrost thaw gradient. Decomposition of soil organic carbon from the Swedish tussock tundra." University of Gothenburg, 11 February 2020, B1078, pp. ii, 1.

- Turetsky, M.R. *et al.* "Carbon release through abrupt permafrost thaw." *Nature Geoscience* **13,** February 2020, pp. 138.