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Limited release of previously-frozen C and increased new peat formation after thaw in permafrost peatlands

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ABSTRACT

Permafrost stores globally significant amounts of carbon (C) which may start to decompose and be released to the atmosphere in form of carbon dioxide (CO_2) and methane (CH_4) as global warming promotes extensive thaw. This permafrost carbon feedback to climate is currently considered to be the most important carbon-cycle feedback missing from climate models. Predicting the magnitude of the feedback requires a better understanding of how differences in environmental conditions post-thaw, particularly hydrological conditions, control the rate at which C is released to the atmosphere. In the sporadic and discontinuous permafrost regions of north-west Canada, we measured the rates and sources of C released from relatively undisturbed ecosystems, and compared these with forests experiencing thaw following wildfire (well-drained, oxic conditions) and collapsing peat plateau sites (water-logged, anoxic conditions). Using radiocarbon analyses, we detected substantial contributions of deep soil layers and/or previously-frozen sources in our well-drained sites. In contrast, no loss of previously-frozen C as CO_2 was detected on average from collapsed peat plateaus regardless of time since thaw and despite the much larger stores of available C that were exposed. Furthermore, greater rates of new peat formation resulted in these soils becoming stronger C sinks and this greater rate of uptake appeared to compensate for a large proportion of the increase in CH_4 emissions from the collapse wetlands. We conclude that in the ecosystems we studied, changes in soil moisture and oxygen availability may be even more important than previously predicted in determining the effect of permafrost thaw on ecosystem C balance and, thus, it is essential to monitor, and simulate accurately, regional changes in surface wetness.

1. Introduction

Soils in the northern circumpolar permafrost region (17.8×10^6 km^2, 0–3 m depth) represent the largest terrestrial carbon store, containing > 1000 Pg C (Hugelius et al., 2014; Tarnocai et al., 2009), which has accumulated over thousands of years (Gorham et al., 2007; Harden et al., 1992; Mackay, 1958; Zoltai, 1995). Permafrost peatlands (histels) occupy more than 1 million km^2 in lowlands of the Arctic and Subarctic and, with thick organic soil horizons, contain disproportionally high amounts of soil carbon per unit area (Hugelius et al., 2014). In uplands and well-drained landscapes, gelisols have thinner organic soil horizons (orthels and turbels) but constitute an even larger stock globally due to their ~7 times greater spatial extent (Hugelius et al., 2014). Although more than half of this C stock is perennially frozen (Hugelius et al., 2014; Tarnocai et al., 2009), a substantial fraction may thaw this century (Brown and Romanovsky,

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2008; Camill, 2005; Harden et al., 2012), decompose and enter the atmosphere as CO_2 or CH_4, potentially exacerbating climate change (Schuur et al., 2015). This permafrost carbon feedback is missing in Earth system models (Ciais et al., 2013) and its inclusion may result in high-latitude ecosystems being predicted to become sources rather than sinks of C during the 21st century (Koven et al., 2011). However, the magnitudes and timings of soil organic carbon (SOC) loss from permafrost are highly uncertain, with estimates of 37–347 Pg C by 2100 (Schaefer et al., 2014). Changes in vegetation and soil C storage are also predicted to have increased in the last decades in the permafrost region and need to be considered along with the loss of permafrost SOC (McGuire et al., 2016). Thus, accurately projecting future rates of CO_2 release from permafrost is essential for predicting the magnitude of this feedback.

The impacts of permafrost thaw at the landscape level strongly depend on the terrain topography and ground-ice characteristics, which influence drainage and moisture conditions in the newly-thawed soils (Jorgenson and Osterkamp, 2005; Osterkamp et al., 2000). In upland and well-drained areas, thaw typically results in deepening of the active layer and as water drains from the system, oxic conditions tend to predominate throughout the soil profile. In contrast, thaw in peatlands that have developed in lowlands with ice-rich permafrost often results in thermokarst landforms characterized by surface subsidence, waterlogging, vegetation change and fast peat accumulation following thaw (Beilman, 2001; Camill, 1999; Turetsky et al., 2007, 2000; Zoltai, 1993). Soil moisture strongly controls the type of decomposition (aerobic vs anaerobic) through the oxygen content in the soil and thus the amount and form (CO_2 and CH_4) of C released (Elberling et al., 2011; Estop-Aragonés et al., 2012; Schädel et al., 2016). A recent analysis of laboratory incubation data suggested that the rates of C release will be greater, and have more effect on the climate, if thaw results in oxic (release as CO_2) rather than anoxic conditions, even after accounting for the potential release of the more powerful greenhouse gas CH_4 under anoxic conditions (Schädel et al., 2016). However, *in situ* observations of changes in ecosystem C storage in Alaska suggest that under anoxic conditions the potential still exists for rapid (within decades) C losses equating to 30–50% of peat plateau C stocks following thaw (Jones et al., 2016; O'Donnell et al., 2012). Given this uncertainty, there is an urgent requirement for *in situ* quantification of rates of previously-frozen C release following thaw in contrasting ecosystems.

Critically, there are no reported measurements of rates of CO_2 release from previously-frozen C following either fire-induced thaw in well-drained forests or thermokarst in peatland plateaus, despite the large spatial extent of these disturbances in the Boreal (Grosse et al., 2011). While permafrost thaw in peatlands can result in clear changes within the ecosystem, thaw in well-drained sites without ice-rich permafrost can be much harder to detect in the landscape. Forest fires, whose frequency and severity have increased during recent decades (Gillett et al., 2004; Kasischke et al., 2010), remove vegetation and surface organic matter, which are important controls on the ground surface energy balance. This can result in rapid warming and substantial deepening of the active layer in uplands and well-drained areas (Burn, 1998; Fisher et al., 2016; Yoshikawa et al., 2002). Thus, paired burnt and unburnt sites offer an opportunity to quantify potential rates of release of previously-frozen C under oxic conditions. Furthermore, as permafrost C is typically thousands of years old (Gorham et al., 2007; Harden et al., 1992; Mackay, 1981; Zoltai, 1995), measuring the radiocarbon (^{14}C) content of the CO_2 released from thawed soil profiles definitively tests whether previously-frozen, aged C (depleted in ^{14}C) contributes substantially to release post-thaw.

In addition, quantifying both the rates of C loss from these sources and the C accumulation rates following thaw is required to quantify the consequences of permafrost thaw on ecosystem C balance. It is well established that permafrost thaw in peatlands results in rapid new peat accumulation (Turetsky et al., 2007) and that this accumulation changes with time since thaw (Camill, 1999). Radiometric dating of peat using ^{210}Pb makes it possible to quantify C accumulation rates for the past ~150 years by assuming a constant supply of atmospheric ^{210}Pb deposited and incorporated in soil (Appleby, 2001; Turetsky et al., 2004). Finally, in terms of determining whether thaw under oxic or anoxic conditions has the greatest impact in terms of changes in global warming potential, any increase in CH_4 flux (Cooper et al., 2017; Turetsky et al., 2007) must also be considered together with the change in C balance.

To determine how the hydrological conditions after permafrost thaw control feedbacks to climate change, we studied the consequences of thaw in peatlands and well-drained fire sites in the sporadic and discontinuous permafrost zones of north-west Canada. We measured fluxes and sources of CO_2, as well as changes in C accumulation rates to quantify the effects on ecosystem C balance, and placed these findings into the context of previously-published research on the rates, and sources, of CH_4 release from the same sites (Cooper et al., 2017). Finally, additional incubations were performed to compare our *in situ* findings with the type of data that are often used to predict the magnitude of the permafrost feedback (Koven et al., 2015). We conclude that in the ecosystems we studied, oxic conditions following thaw are required for permafrost thaw to represent a strong positive feedback to climate change.

2. Materials and methods

2.1. Site selection

The fastest and greatest extent of thaw is expected within the discontinuous and sporadic permafrost zones, where permafrost temperatures are close to 0 °C (Brown and Romanovsky, 2008; Camill, 2005). Therefore, we studied peatlands and well-drained sites in the sporadic permafrost zone in Yukon (2013) and in the extensive discontinuous permafrost zone (Brown et al., 1997) in Northwest Territories, NWT (2014). Research was undertaken at four study sites: a peatland near Teslin (Yukon peatland), a peatland near Yellowknife (NWT peatland), an upland forest near Whitehorse (Yukon well-drained forest), and a forest near Behchoko (NWT well-drained forest). The mean annual air temperature (MAAT, 1981–2010) for the Yukon peatland was −0.6 °C, with monthly averages ranging from −17.1 °C in January to 14.1 °C in July and the mean annual precipitation (MAP) was 346 mm (Environment Canada, 2015). For the Yukon well-drained forest, the MAAT was −1.4 °C, with monthly averages ranging from −18.2 °C in January to 13.9 °C in July, and the MAP was 228 mm. For the NWT sites, the MAAT was −4.3 °C, with monthly averages ranging from −25.6 °C in January to 17.0 °C in July, and the MAP was 289 mm.

The Yukon peatland study site (Fig. 1a) contained an isolated permafrost peat plateau fringed by a thermokarst wetland (approximate size 30 × 40 m) located near MP788 (Alaskan Highway Milepost), approximately 20 km southeast of Teslin in the Yukon Territory (60°05′27.5″N, 132°22′06.4″W). The peat plateau was elevated up to 1.5 m above the surrounding wetland, with electrical resistivity probe measurements suggesting that permafrost thickness was 15–18 m in the higher parts of the plateau (Lewkowicz et al., 2011). The thermokarst wetland was dominated by hydrophilic sedges (*Carex rostrata* Stokes), which resulted in the accumulation of sedge-derived peat since thaw. The mean active-layer thickness (ALT) in 2013 in the plateau was 49 cm, while thaw depths exceeded 160 cm in the wetland. The plateau collapsed ~55 yr ago and ~50 cm of pure sedge peat had accumulated since then. A layer of tephra identified as White River Ash present near the base of the active layer (~38 cm) in the peat plateau indicates that the minimum age of the organic matter at the top of the current permafrost layer was 1200 yr BP (Clague et al., 1995). The White River tephra layer (1200 yr BP) was observed at a shallower depth (21 cm) in the Margin of the wetland, where peat was more compacted, and in two Wetland centre cores at 55 and at 102 cm. In this site, we investigated the contribution of deep SOC-derived CO_2 using radiocarbon