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Investigating the controls on soil organic matter decomposition in tussock tundra soil and permafrost after fire

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ABSTRACT

Rapid warming in Arctic ecosystems is resulting in increased frequency of disturbances such as fires, changes in the distribution and productivity of different plant communities, increasing thaw depths in permafrost soils and greater nutrient availability, especially nitrogen. Individually and collectively, these factors have the potential to strongly affect soil C decomposition rates, with implications for the globally significant stores of carbon in this region. However, considerable uncertainty remains regarding how C decomposition rates are controlled in Arctic soils. In this study we investigated how temperature, nitrogen availability and labile C addition affected rates of CO_2 production in short (10-day for labile C) and long-term (1.5 year for temperature and N) incubations of samples collected from burned and unburned sites in the Anaktuvuk river burn on the North Slope of Alaska from different depths (organic horizon, mineral horizon and upper permafrost). The fire in this region resulted in the loss of several cms of the organic horizon and also increased active layer depth allowing the impacts of four years of thaw on deeper soil layers to be investigated. Respiration rates did not decline substantially during the long-term incubation, although decomposition rates per unit organic matter were greater in the organic horizon. In the mineral and upper permafrost soil horizons, CO_2 production was more temperature sensitive, while N addition inhibited respiration in the mineral and upper permafrost layers, especially at low temperatures. In the short-term incubations, labile C additions promoted the decomposition of soil organic matter in the mineral and upper permafrost samples, but not in the organic samples, with this effect being lost following N addition in the deeper layers. These results highlight that (i) there are substantial amounts of labile organic matter in these soils (ii), the organic matter stored in mineral and upper permafrost in the tussock tundra is less readily decomposable than in the organic horizon, but that (iii) its decomposition is more sensitive to changes in temperature and that (iv) microbial activity in deeper soil layers is limited by labile C availability rather than N. Collectively, these results indicate that in addition to the loss of C by combustion of organic matter, increasing fire frequency also has the potential to indirectly promote the release of soil C to the atmosphere in the years following the disturbance.

1. Introduction

Although northern permafrost soils comprise only 20% of the global land area, they store approximately 50% of the global belowground C pool (Schuur et al., 2008; Tarnocai et al., 2009). The total C stored in these soils is estimated by Tarnocai et al. (2009) at 1672 Pg, which is approximately twice the amount of C in the atmosphere at present (IPCC, 2013). Given the high rates of warming predicted for high northern latitudes, there are concerns that some of this C may be released to the atmosphere if the permafrost starts to thaw.

The climate has already changed substantially in many areas of the Arctic (0.6 °C per decade over the last 30 years, IPCC, 2013) and as a result wildfires have become an increasingly important factor in the tundra biome during the last 50 years (Higuera et al., 2008), releasing large amounts of C (Mack et al., 2011). Fire frequency is

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expected to increase further in the 21st century as a result of climate change (Higuera et al., 2008). In 2007, the Anaktuvuk River fire burned over 1000 km^2 of tundra on the North Slope of the Brooks Range in Alaska (USA), doubling the cumulative area burned in this region over the past 50 years. The magnitude of the C lost by the Anaktuvuk River fire (ca. 2 Tg C) is similar to the annual net C sink for the entire Arctic tundra biome averaged over the last quarter of the twentieth century (Mack et al., 2011). This fire also enhanced active layer thickness by removing insulating plant biomass and exposing surfaces with low albedo (Jones et al., 2009; Rocha and Shaver, 2011). Although it is clear that tundra fires have an immediate impact on landscape C stocks, there may also be indirect, less straightforward effects of increased fire frequency on the tundra C balance.

Although the lack of woody biomass reduces the amount of charcoal entering the soil compared with boreal forest fires (e.g. O'Donnell et al., 2009), the ash from the fire and reduction in plant nutrient uptake can result in big increases in inorganic nutrient availability (Jiang et al., 2015) which may affect decomposition rates, especially in the surface horizons. Fire removes part of the organic horizon and also increases total active layer thickness (Rocha and Shaver, 2011), which results in the active layer now including soil layers that previously remained frozen. To determine the rate at which permafrost C may be transferred to the atmosphere it is essential to determine how decomposable the soil organic matter (SOM) in these deep horizons is and which factors can promote or reduce rates of C release (Schädel et al., 2014). Kinetic theory suggests that the temperature sensitivity of decomposition should be greater for more slowly decomposing recalcitrant organic matter and there is empirical support for this hypothesis (Hartley and Ineson, 2008). However, there is also growing recognition that decomposition rates may be controlled more by physical and chemical protection mechanisms in soils (Dungait et al., 2012; Schmidt et al., 2011) than substrate quality and therefore it is unclear how temperature sensitive the decomposition of old permafrost carbon will be. Studies to date there have produced contrasting findings regarding whether permafrost C is more (Wang et al., 2013), less (Waldrop et al., 2010) or as (Moni et al., 2015) decomposable as SOM in the active layer. With models currently tending to apply the same temperature functions to all soil layers (Burke et al., 2012; Koven et al., 2011), it is important that the temperature sensitivity of the decomposition of permafrost versus non-permafrost SOM is investigated further (Moni et al., 2015; Schädel et al., 2014).

Furthermore, permafrost thaw has been shown to increase N availability (Natali et al., 2012) which may have major impacts on soil organic matter turnover rates, as well as vegetation communities. In moist acidic tundra, Mack et al. (2004) observed a substantial loss of C from deep soil layers following long-term *in situ* fertilisation which was attributed to the nutrients promoting microbial activity. If microbial activity is constrained by the low N availability then thawing permafrost could further increase microbial activity, with Sistla et al. (2012) demonstrating that microbial biomass production and enzyme activity can both be increased by N addition, albeit that study was confined to the top 5 cm of tussock tundra soil. On the other hand, the effects of N addition on decomposition have been shown to depend on the type of organic matter with the decomposition of labile organic matter promoted by N addition (Neff et al., 2002; Knorr et al., 2005a; Lavoie et al., 2011), but the decomposition of low quality (Knorr et al., 2005a) or mineral-associated organic matter potential inhibited by N addition (Neff et al., 2002). Therefore, it is essential to investigate whether increasing N availability stimulates decomposition by increasing microbial activity or whether greater N availability can inhibit the decomposition of the large slowly decomposing SOM pools, and whether these effects change with soil depth.

Finally, as the plant community recovers after fire, previously frozen organic matter will come into contact with plant roots and therefore new C inputs. It has previously been shown that an increase in the availability of labile C in Arctic soils can increase the decomposition of existing SOM (e.g. Hartley et al., 2010; Wild et al., 2014). There are multiple theories proposed to explain these responses. Simple sugar additions may activate previously substrate-limited microbial communities, or stimulate decomposition if microbial nutrient limitation increases as a result of any increase in the rate of microbial or decomposer biomass production (Blagodatskaya and Kuzyakov, 2008). Therefore, these effects may depend on soil nutrient availability and/or the availability of readily decomposable SOM making it difficult to predict how decomposition rates in different soil layers will be controlled.

In summary, the medium-term impacts of fire on C release from the decomposition of SOM is not fully understood due to indirect effects on thaw depth, soil temperature, nutrient and labile C availability. In this study, we addressed this uncertainty by investigating potential decomposition controlling mechanisms. This was done by carrying out a long-term (1.5 year) incubation to investigate the effects of N availability and temperature sensitivity on decomposition rates, and a short-term incubation (10 days) to determine the effects of N vs labile C addition with depth in the soil. We hypothesized 1) that decomposition will be more temperature sensitive at greater depths due to the greater substrate recalcitrance (Conant et al., 2008; Hartley and Ineson, 2008); 2) that increased N availability will increase rates of SOM decomposition throughout the soil profile, but the effect would be greatest in the surface horizons due to the greater availability of high quality, readily decomposable C; 3) labile C (glucose) addition would increase the rate of existing SOM decomposition, and that these effects will be greatest in mineral and upper permafrost layers if the decomposers can use this extra energy to break down more recalcitrant C compounds.

2. Materials and methods

2.1. Study area and soil sampling

Samples were taken in from the Anaktuvuk River Burn, situated on the North Slope of the Brooks Range, Alaska, approximately 23 km northwest of Toolik Field Station (68.5833 °N, 149.7167 °W). The Anaktuvuk River forms the Western boundary of the Burn, while the Itkillik River forms the Eastern boundary. This region is underlain by continuous permafrost. Mean annual temperature is approximately −10 °C and mean annual precipitation is 300 mm. Before the 2007 fire, 54% of the vegetated area within the burn perimeter was classified as upland moist acidic tundra, 15% as moist non-acidic tundra and 30% as shrubland (Mack et al., 2011). The dominant species in this acidic tundra is Eriophorum vaginatum.

In 2011, four years after the fire, samples were taken from severely burnt (following the classification in Jones et al., 2009) and adjacent unburnt sites to a depth of 45 cm, sampling the organic, mineral, and upper permafrost horizons in both sites. Three replicates (i.e., three spatially separated sample profiles) were taken in the burnt and unburnt area respectively (Fig. 1). The burnt soil profiles lost on average 6 cm of the soil organic layer (Mack et al., 2011). The sites are well described in Rocha and Shaver (2011) and Bret-Harte et al. (2013).

2.2. Sample processing

To remove roots and other larger organic parts, the soils were