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Decreases in soil moisture and organic matter quality suppress microbial decomposition following a boreal forest fire

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ABSTRACT

Climate warming is projected to increase the frequency and severity of wildfires in boreal forests, and increased wildfire activity may alter the large soil carbon (C) stocks in boreal forests. Changes in boreal soil C stocks that result from increased wildfire activity will be regulated in part by the response of microbial decomposition to fire, but post-fire changes in microbial decomposition are poorly understood. Here, we investigate the response of microbial decomposition to a boreal forest fire in interior Alaska and test the mechanisms that control post-fire changes in microbial decomposition. We used a reciprocal transplant between a recently burned boreal forest stand and a late successional boreal forest stand to test how post-fire changes in abiotic conditions, soil organic matter (SOM) composition, and soil microbial communities influence microbial decomposition. We found that SOM decomposing at the burned site lost 30.9% less mass over two years than SOM decomposing at the unburned site, indicating that post-fire changes in abiotic conditions suppress microbial decomposition. Our results suggest that moisture availability is one abiotic factor that constrains microbial decomposition in recently burned forests. In addition, we observed that burned SOM decomposed more slowly than unburned SOM, but the exact nature of SOM changes in the recently burned stand are unclear. Finally, we found no evidence that post-fire changes in soil microbial community composition significantly affect decomposition. Taken together, our study has demonstrated that boreal forest fires can suppress microbial decomposition due to post-fire changes in abiotic factors and the composition of SOM. Models that predict the consequences of increased wildfires for C storage in boreal forests may increase their predictive power by incorporating the observed negative response of microbial decomposition to boreal wildfires.

1. Introduction

The soils of boreal forests store an estimated 150–191 Pg carbon (C), which accounts for approximately 20% of global soil organic C (Jobbagy and Jackson, 2000; Tarnocai et al., 2009). Given the large amount of C stored in the soils of boreal forests, there is substantial interest in predicting the impact of climate warming on soil C stocks in this region. Surface temperatures in boreal ecosystems have increased by approximately 2 °C in the past 100 years, and these ecosystems are anticipated to warm by an additional 3–8 °C in the next century (Wendler and Shulski, 2009; IPCC, 2013). One anticipated consequence of climate warming in boreal forests is an increase in wildfire activity.

Fires are a chronic global disturbance in boreal forests, but North American and Eurasian boreal forests experience distinct fire regimes. In North America, boreal forest fires are typically high-intensity crown fires that kill most trees, combust organic matter in surface soils, and initiate century-long vegetation succession. In contrast, Eurasian boreal forests fires are typically low-intensity surface fires that do not kill healthy trees (Wooster and Zhang, 2004; de Groot et al., 2013a; Rogers et al., 2015). Climate warming and summer drought are predicted to shift boreal forest fire dynamics in North America to a fire regime characterized by a greater number of extreme fire years with larger fires that burn at higher severity (Gillett et al., 2004; Turetsky et al., 2011; de Groot et al., 2013b). Models of future wildfire activity predict that the burned area in North American boreal forests could increase 2–5

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times by the end of the 21st century (Flannigan et al., 2005; Balshi et al., 2009; Euskirchen et al., 2009). Increases in boreal wildfire activity that result from climate warming may alter soil C stocks in boreal forests through direct and indirect mechanisms. Combustion of surface soils is a direct mechanism through which boreal forest fires alter soil C stocks. Indirectly, longer term changes in soil C stocks that result from increased boreal forest fires will be primarily mediated by post-fire changes in microbial decomposition.

Microbial decomposition governs the amount of soil C stored in an ecosystem, and the rate of decomposition is regulated by abiotic factors (i.e., temperature, moisture), the quantity and quality of soil organic matter (SOM) available for decomposition, and the soil microbial community (Swift et al., 1979; Aerts, 1997; Cornwell et al., 2008; Prescott, 2010). Classic ecosystem theory of secondary succession predicts that microbial decomposition increases following boreal forest fires (Harmon et al., 2011; Chapin et al., 2011b). Hypothesized post-fire increases in microbial decomposition are based on two critical assumptions. First, boreal forest fires create abiotic conditions that are more favorable to decomposition than the pre-fire abiotic conditions. Second, boreal forest fires increase the pool of labile C that is available to decomposer microbes. One estimate of microbial decomposition following a boreal forest fire concluded that the post-fire stimulation of microbial decomposition released as much C to the atmosphere as combustion emissions during the fire (Richter et al., 2000). Post-fire decomposition increases of this magnitude could substantially reduce soil C stocks and create a positive feedback between climate warming, wildfire occurrence, and C emissions from post-fire microbial decomposition.

However, hypothesized post-fire increases in microbial decomposition align poorly with the observed response of soil microbial communities to boreal forest fires. Numerous studies have found that boreal forest fires decrease soil microbial biomass (Pietikainen and Fritze, 1995; Smith et al., 2008; Dooley and Treseder, 2012). Moreover, the recovery of microbial biomass following boreal forest fires can require more than a decade (Holden et al., 2013). Consistent with decreases in microbial biomass, the activity of microbial extracellular enzymes has been shown to decline following boreal forest fires (Waldrop and Harden, 2008). Furthermore, additional studies that have measured litter decomposition in burned and unburned forests have found slower rates of litter decay in recently burned stands (Pietikainen and Fritze, 1993; Brennan et al., 2009; Holden et al., 2013). These observations call into question hypothesized post-fire increases in microbial decomposition and the responsible mechanisms.

Microbial decomposition is predicted to increase following boreal forest fires in part because wildfires are assumed to create abiotic conditions that are favorable for decomposition. Cold temperatures and water-saturated soils in late successional boreal forests typically constrain the activity of decomposer microbes and lead to slow rates of decomposition (Van Cleve et al., 1983). Boreal forest fires of North America increase the amount of solar radiation that reaches the soil surface, because fires reduce canopy thickness and remove the insulating moss groundcover. As a consequence, growing season soil temperatures in the top 10 cm of soil in recently burned stands are typically 5–10 °C higher than in late successional stands (Treseder et al., 2004; Liu et al., 2005). Post-fire increases in soil temperature can also be accompanied by decreases in soil moisture (Holden et al., 2013). Microbial decomposition is often highest at intermediate moisture levels, when soils are dry enough that oxygen availability is not limited but not so dry that microbes have insufficient access to water (Chapin et al., 2011a). Thus, post-fire changes in microbial decomposition may depend on the degree of soil drying following the fire.

Changes in the quantity and quality of SOM following boreal forest fires may also influence post-fire microbial decomposition. Here, we define SOM following Baldock and Broos (2011) as the sum of all natural and thermally altered biologically derived organic materials found in the soil or on the soil surface. Fires can potentially increase SOM through C inputs from root death and partially combusted aboveground vegetation. In addition, soil nutrients often increase after fires due to the deposition of nutrient rich ash on the soil surface (Wan et al., 2001; Harden et al., 2004). Increased nutrient availability in nutrient-poor boreal soils may alleviate microbial nutrient limitation and stimulate decomposition. The higher quality litter of early successional plants relative to late successional plants might also stimulate microbial decomposition. On the other hand, boreal forest fires usually combust feathermoss groundcover and the uppermost portion of the organic horizon and thus may actually reduce the pool of SOM that is available for decomposition (Turetsky et al., 2011). There is also evidence that fire combusts the more labile components of SOM and that the residual SOM is more enriched in complex molecules that are difficult for microbes to decompose (Czimczik et al., 2003; Harden et al., 2004; Neff et al., 2005). Finally, although early successional plant litter is often of higher quality, total plant litter inputs to soil are reduced in the first few years following boreal forest fires as vegetation recovers (Mack et al., 2008). The net response of microbial decomposition to post-fire changes in the quality and quantity of SOM is unclear.

In addition to abiotic factors and the characteristics of SOM, the soil microbial community exerts direct biotic control over decomposition. Indeed, recent studies have demonstrated that microbial community composition directly affects decomposition rates and CO_2 production (Allison et al., 2013; Reed and Martiny, 2013). Boreal forest fires have previously been shown to alter the composition of the soil microbial community. For example, recently burned stands in interior Alaska were dominated by ascomycete fungi, while late successional stands had a high abundance of basidiomycete fungi (Holden et al., 2013). Bacterial community composition in boreal forests is also sensitive to disturbance by fire (Smith et al., 2008; Xiang et al., 2014). However, the consequences of post-fire changes in soil microbial communities for decomposition have not been previously investigated.

Overall, the response of microbial decomposition to boreal forest fires remains uncertain. This uncertainty hinders our ability to accurately predict C cycle and climate feedbacks that arise from increased wildfire activity (Allison and Treseder, 2011). Therefore, the goals of our study were to understand how microbial decomposition changes following high-intensity crown fires in boreal forests of North America and to examine the mechanisms that govern post-fire changes in microbial decomposition. We used a reciprocal transplant between a recently burned boreal forest stand and a late successional boreal forest stand to independently manipulate soil abiotic conditions, SOM, and the microbial community. We then measured the consequences for microbial decomposition. Contrary to classic ecosystem theory of secondary succession, but in line with the findings from recent studies, we hypothesized that post-fire changes in abiotic conditions would reduce the rate of microbial decomposition. In addition, we predicted that changes in SOM following boreal forest fires would negatively affect microbial decomposition. Finally, we expected that post-fire microbial community changes would influence decomposition.

2. Materials and methods

2.1. Study sites

Our study was conducted in a boreal forest ecosystem in interior Alaska near the Pogo Gold Mine in the Tanana Valley State Forest approximately 100 km east of Fairbanks. The local climate is cold