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Physico-chemical and functional characteristics of soil charcoal produced at five different temperatures

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ABSTRACT

The intensity of boreal forest wildfires is highly variable, such that natural wood charcoal can be produced at different peak temperatures. This, in turn, may have consequences on the physico-chemical and functional properties of the charcoal that is returned to soil. We report on a microcosm study where black spruce wood charcoal produced at five peak temperatures (450, 550, 650, 750 and 850 °C) was added to forest soils, and subsequently incubated at room temperature, with and without additions of condensed tannins and/or protein. A fourth experimental factor was added to this full factorial design, which comprised the mixing of soil so as to simulate mechanical scarification in the field. Increasing the charcoal production temperature resulted in higher %C and lower %O and %H, suggesting an increase in aromatic structures. Specific surface area was negligible at 450 °C, was about 50 $m^2\ g^{-1}$ at 550 °C, and was 260–300 $m^2\ g^{-1}$ at the three highest temperatures. At these higher charcoal production temperatures, 85–90 % of total surface area was attributed to pores <20 nm. The incubation demonstrated a decline in soil basal respiration (BR) with charcoal addition, with increasing charcoal production temperature and with tannin additions, whereas BR increased with protein addition and with soil mixing. Charcoal addition reduced soil microbial biomass (MB), however charcoal production temperature had no effect on MB. Consequently, we observed a decrease in microbial metabolic quotient (qCO_2) with increasing charcoal production temperature, which reflected the decline in BR. Increasing charcoal production temperature increased net NH_4^+ production in the non-mixed soils, but decreased net NH_4^+ production in the mixed soils. Protein additions increased net NH_4^+ production more so in the mixed than in the non-mixed soils. Our results thus show that charcoal production temperature has a marked and significant effect on soil C and N cycling, and that these effects are substantially modified by soil mixing. This further suggests that changes in boreal forest fire intensity, due to anthropogenic changes in tree species composition or climate, could affect the dynamics of forest regeneration through variations in the chemical and functional properties of the charcoal, and that these effects may be substantially modified by post-fire silvicultural treatments such as mechanical scarification.

1. Introduction

Forest fire is the most common natural disturbance and an essential driver of ecological succession in boreal forest ecosystems (e.g., Heinselman, 1981; Payette, 1992). Post-fire forest regeneration and successional pathways may differ widely among sites (Mallik, 1994; Kasischke et al., 2000; Lecomte et al., 2006), due in part to the structure, age or composition of the pre-disturbance stand. For example, canopy gaps created by early stand thinning or old-growth tree mortality have been associated with an increased presence of ericaceous shrubs such as *Kalmia* (*Kalmia angustifolia* L.) or Ledum (*Rhododendron groenlandicum* (Oeder) Kron and Judd) in the understory (e.g. Mallik, 1994). These rhizomatous shrubs produce underground vegetative buds that may or may not be destroyed by wildfire, depending on depth of organic matter burned. Following wildfire, the spread of these shrubs may check the growth of regenerating trees on some sites and maintain heathland conditions for many years following disturbance (Damman, 1971; Mallik, 1994; Hébert and Thiffault, 2011). Several studies have suggested that *Kalmia*-induced growth check of black spruce (*Picea mariana* (Mill.) B.S.P.) seedlings could be the result of lower soil microbial turnover (Bradley et al., 1997; Bradley et al., 2000) and lower soil mineral N supply (Bradley et al., 1997; Le Bel et al., 2008), due to high concentrations of condensed tannins

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in *Kalmia* litter (Joanisse et al., 2007, 2009). These tannins were shown to precipitate soil proteins that would otherwise be mineralized to supply black spruce seedlings with N (Bradley et al., 2000; Joanisse et al., 2009). *Kalmia*, on the other hand, may gain access to the N sequestered in tannin-protein precipitates due to enzymes produced by their associated ericoid mycorrhizae (Joanisse et al., 2009).

Climate change can affect forest fire regimes in a number of ways, and has thus been the focus of several modeling studies aimed at predicting future forest dynamics (e.g., Shabbar et al., 2011). Climate induced changes in fire intensity (i.e., the energy, or heat, released per unit area – Keeley, 2009) may affect post-fire forest regeneration and successional pathways (Heinselman, 1981; Arseneault, 2001). Ryan (2002) estimated wildfire intensity to be highly variable, with temperatures ranging from 300 °C to 1000 °C. High intensity wildfires tend to reduce ericaceous shrubs (Grondin and Cimon, 2003; Purdon et al., 2004; Lecomte et al., 2006) because of a higher mortality of the rhizomatous budbank. This is turn may result in higher C and N cycling following the establishment of early seral plant communities. Fire intensity may also affect soil C and N cycling by affecting the quality of the charcoal that is produced. For example, the porosity of charcoal tends to increase with increasing temperature at which it is produced (Yu et al., 2006; Gundale and DeLuca, 2006). Higher porosity translates into higher surface area to which dissolved soil molecules, such as tannins and other phenolics, may be adsorbed (Zackrisson et al., 1996). Evidence that charcoal enhances soil N availability was thus given in a few independent studies (e.g., Wardle et al., 1998; De Luca et al., 2006). To our knowledge, only one such study (i.e., Gundale and DeLuca, 2006) compared the effect of charcoal produced at two different temperatures (350 °C and 850 °C) on soil C and N cycling. A similar study using more intermediate temperatures would allow the detection of trends and thresholds.

Mechanical scarification is a post-disturbance silvicultural treatment that may abate the growth check of conifer seedlings by ericaceous shrubs. This treatment is a disk-trenching operation whereby the organic surface soil is plowed and buried, while a trough is created exposing deeper mineral soil layers. Scarification was shown to reduce *Kalmia*-induced growth check of black spruce seedlings when the latter were established in the exposed mineral soil (Richardson, 1981; Mallik, 1994; Thiffault, 2003). It is generally assumed that this results from a temporary isolation from *Kalmia*'s zone of influence, resulting in lower competition for nutrients and lower concentrations of litter tannins in the immediate vicinity of black spruce seedlings (Titus et al., 1995; Prévost, 1996; Yamasaki et al., 1998). In the present study, we posit that scarification on fire-disturbed sites may also improve soil nutritional quality by increasing the surface of contact between the charcoal carbon and soil compounds, which should increase the adsorption of soil tannins and the cycling of C and N.

Another silvicultural treatment that may abate the growth check of conifer seedlings by ericaceous shrubs, is the application of mineral N fertilizers (Prescott et al., 1993; Titus et al., 1995; Bradley et al., 2000; Lebel et al., 2008). There is evidence that the root systems of certain conifer species such as black spruce are more efficient at capturing fertilizer N (i.e., N absorbed per unit root mass) than the root systems of competing ericaceous shrubs (Thiffault et al., 2004). The positive effect of mineral N fertilization on tree growth, in ericaceous-dominated forest clearcuts, may persist for many years after treatment (Weetman et al., 1987; LeBel et al., 2008). For example, Bradley et al. (2000) showed a sustained improvement in conifer tree growth 13 years after fertilizing a cutover dominated by ericaceous shrubs, concomitant with higher needle N concentrations as well as higher net and gross soil N mineralizing rates. This suggested that N fertilization had improved long-term site nutritional quality by the repeated recycling of fertilizer N via litterfall and soil microbial turnover. This long-term positive effect of mineral N fertilization on nutrient cycling could be simulated, therefore, by adding protein to soil as a surrogate for litter and microbial organic N compounds.

We report on a microcosm study in which mineral and organic soils were jointly incubated for 8 weeks with a full factorial array of treatments that included the addition or exclusion of *Kalmia* tannins, protein, and wood charcoal produced at 5 different temperatures. A fourth experimental factor comprised the physical arrangement (mixed vs. non-mixed) of the soil, or of the soil + charcoal, designed to simulate the effect of scarification. We examined the effects of these treatments on net soil C and N mineralization and soil microbial biomass. We hypothesized that wood charcoal, protein and soil mixing would increase, whereas tannins would decrease, C and N mineralization and MB. We also hypothesized that increasing the temperature at which the charcoal was produced would increase C and N mineralization and MB. Our overall goal was to help predict how changes in fire regimes (in this case fire intensity), as predicted by certain climate change models, could impact soil C and N cycling, and ultimately the growth and sustainability of forests under different management scenarios.

2. Materials and methods

2.1. Soil and charcoal material

Bulk samples (50 kg) of organic forest floor (F-layer) and of surface mineral soil (0–30 cm) were collected from two mature black spruce-feathermoss stands located near the Town of Forestville (48°44′ N, 69°05′ W), in the black spruce-feathermoss biogeoclimatic zone (Morneau and Landry, 2007). The soils in each stand were characterized as Orthic Humic Podzols, according to the Canadian Soil Classification System (Soil Classification Working Group, 1998). The understory is dominated by ericaceous shrubs (*K. angustifolia* L., *R. groenlandicum* (Oeder) Kron & Judd, *Vaccinium angustifolium* Ait.) and various mosses (*Sphagnum girgensohnii* (Russow), *Pleurozium schreberi* (Brid.) Mitt.). Soils from both sites were pooled according to soil layer, sieved (5 mm mesh) to remove roots and coarse debris, and stored at 4 °C. Soil pH (soil:water = 1:3 mineral soil, 1:10 = organic soil) was measured using a hydrogen electrode. Total C and N were measured by high temperature combustion followed by gas analysis, using a Vario Macro C&N analyzer (Elementar Analysensysteme Corp., Hanau, Germany). The textural classes of the mineral soil were determined by particle-size analyses using the Boyoucous hydrometer method (Bouyoucos, 1936). Mehlich extractible base cations (Na, Ca, Mg, K) were analyzed with an AAnalyst 100 atomic absorption spectrometer (Perkin–Elmer Corp., Waltham, MA) whereas Mehlich extractible P (Mehlich, 1984) was analyzed colorimetrically with a spectrophotometer (Spectro 1200, UNICO Corp., Princeton, NJ). Results from these preliminary soil analyses are shown in Table 1.

We produced charcoal from untreated black spruce boards (5 cm × 10 cm × 3 m) purchased from a local lumber dealer. Boards were cut into 30 cm long sections, were placed four at a time in a stainless steel pan and heated for 4 h in a toaster oven set at 180 °C in order to release volatile substances. After cooling to room temperature, the pre-charred wood sections were placed four at a time into stainless steel beakers with a lid. Each beaker was transferred into a muffle furnace, and furnace temperature was then increased to either 450 °C, 550 °C, 650 °C, 750 °C or 850 °C. Each peak temperature was maintained for 30 min, after which the furnace was turned off. Once cooled to room temperature, charred wood sections produced at similar temperatures were pooled