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Combined influence of fire and salvage logging on carbon and nitrogen storage in boreal forest soil profiles

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ABSTRACT

Boreal forest soils are a significant component of the global C cycle. Although wildfire and subsequent salvage logging are major disturbances in this ecosystem, their combined influence on soil organic carbon (SOC) and total soil nitrogen (N) storage is poorly understood. Our objective was to investigate the recent influence of fire and post-fire salvage logging on SOC and total soil N stocks and distribution in the profile of boreal forest soils. We measured SOC and total N concentrations, bulk density and pH of organic, surface mineral (0–15 cm depth) and subsurface mineral (15–40 cm depth) soil horizons on 14 different fires (burned 2005–2007) in Quebec, Canada. Each site comprised three treatments: a control stand (CTR), a recently burned (<7 years) stand that was not salvaged logged (B-NL) and a recently burned (<7 years) stand that was salvage logged (B-L) within 2 years after the fire. Our results showed that fire-affected stands had less SOC and total N stored in organic horizons, and that post-fire salvage logging reduced SOC concentration in the organic horizon, but promoted SOC and total N enrichment in the subsurface mineral soil. We conclude that mechanical disturbance of recently burned stands can contribute to the mixing of the forest floor and organic matter with the mineral soil, and influence the depth distribution of SOC and total N in the soil profile. When the entire soil profile was considered, SOC and total N stocks were equivalent in burned versus burned and salvage-logged sites. Further research should focus on how disturbance type and intensity influence the molecular nature of soil organic matter and the mechanisms by which SOC and total soil N are retained in the different soil horizons.

1. Introduction

The boreal forest ecosystem plays a critical role in the global C budget given the large amount of C stored in organic and mineral soil horizons (Apps et al., 1993; Jobbágy and Jackson, 2000; Tarnocai et al., 2009; DeLuca and Boisvenue, 2012). Wildfire is the major natural driver of ecosystem processes controlling C storage in boreal forests (Kasischke et al., 1995) while harvesting is the principal anthropogenic disturbance. However, the combined impact of fire and subsequent harvesting of burned stands (salvage logging) on SOC and total soil N in the boreal forest remains poorly understood (Smith et al., 2000; Seedre et al., 2011).

Wildfire and logging as individual disturbances can contribute to decreases in SOC and total N storage through combustion of organic matter, volatilization, deterioration of soil structure and erosion, and alteration of litter inputs and decomposition rate (Smith et al., 2000; Certini, 2005; Bormann et al., 2008). However, fire can potentially increase soil C and N by facilitating greater incorporation and stabilization of charcoal in the mineral soil (Giovannini et al., 1987; Gavin, 1993; DeLuca and Aplet, 2008). In addition, site preparation following logging can increase root penetration, reduce soil bulk density and increase SOC and soil N storage in subsurface soil layers (Nordborg et al., 2006). Logging after fire reduces the vegetation canopy and litter layers, and affects soil microclimate, decomposition, ecosystem carbon uptake capacity, soil microbial communities and nutrient cycling (Brais et al., 2000; Lindenmayer and Noss, 2006; Serrano-Ortiz et al., 2011; Jennings et al., 2012; Marañón-Jiménez and Castro, 2013). Moreover, post-fire salvage logging can reduce organic matter input to the soil by removing the standing dead stems that would eventually fall and contribute to SOC storage (Smith et al., 2000; DeLuca and Aplet, 2008; Moroni et al., 2010; Seedre et al., 2011). In a recent synthesis on the effect of disturbance on Canadian boreal soils, Maynard et al. (2014) found that individually, fire and harvesting were not causing depletion of soil N in coniferous boreal soils. Nevertheless, the cumulative impact of disturbances was identified as a main knowledge gap.

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Post-fire salvage logging is commonly practiced in the boreal forest within two years after fire, in order to maximize potential fiber harvest before serious deterioration of burnt trees occurs, and to facilitate replanting operations (Lindenmayer and Noss, 2006). However, few studies documented the impact of salvage logging on SOC and soil total N stocks. In the Sierra Nevada mixed conifer forest, contradictory results were obtained, with post-fire logging causing either gains [Johnson et al. (2005) on three sites, due to N-fixing species] or losses [Powers et al. (2013) on one fire] in SOC and total N in surface and subsurface mineral soil horizons. Virtually no data are published in the scientific literature to verify this potential combined impact in managed boreal forests. Fire frequency in this region of North America is expected to increase in response to climate change (Girardin et al., 2013) and therefore, the impact of post-fire salvage logging on SOC and total N storage and distribution in the profile of boreal soils needs further investigation.

Major wildfire activity occurred in 2005–2007 in the boreal forest of Quebec (Canada) burning 1.2 M ha of forest, which represents 12% of the total area burned over the past 36 years [Ministère des Ressources Naturelles (MRN), 2010]. About 16% of the area burned in 2005–2007 was salvage logged (MRN, personal communication). This provided a unique occasion to study the impact of post-fire salvage logging on a large number of fires across an east–west transect of over 600 km in the boreal forest; many of the sites were only temporarily accessible. In this context, our objective was to investigate the recent influence (5–7 years) of fire and post-fire salvage logging on SOC and total N in the organic, surface mineral (i.e., 0–15 cm depth) and subsurface mineral (i.e., 15–40 cm depth) horizons of boreal soils. We hypothesized that fire would reduce SOC and total N storage and concentration and that the combined effect of fire and salvage logging would contribute to enhanced SOC and total N losses. Although we expected a greater response to fire and post-fire salvage logging in organic and surface mineral horizons, we also expected to observe modifications in subsurface mineral horizons.

2. Methods

2.1. Description of study sites and experimental design

Fourteen (14) different fires were chosen along a longitudinal gradient (from 68.98 to 76.56°W) near latitude 50°N in Quebec, Canada (Fig. 1 and Table 1). Black spruce [*Picea mariana* (Mill.) BSP] dominated all stands, with a variable component of jack pine (*Pinus banksiana* Lamb.) as a second canopy species. Ericad shrubs and feathermosses dominated the understory, with deciduous shrubs and herbaceous plants being present in less important proportions. Soils of the study sites were classified as Humo-Ferric or Ferro-Humic Podzols according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998), which corresponds with Orthic Podzol according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). All stands were located on mesic sites at an altitude between 268 and 426 m above sea level with mean annual temperature and precipitation of −0.8 °C and 938 mm, respectively.

Each site comprised (1) an unburned stand that served as the control (CTR), (2) a burned stand that was not salvage logged (B-NL) and (3) a burned stand that was salvage logged (B-L) within 2 yr after the fire. All fires were of lightning origin (in years 2005–2007), lasting between 23 and 43 days. Fires occurred in the spring, and burnt areas ranged from ~300 to ~30,300 ha (Table 1). The 14 burned and salvage logged stands were either harvested ($n = 6$), scarified following harvesting ($n = 3$) or scarified and replanted ($n = 5$) to black spruce or jack pine following harvesting. The experimental unit consisted of a 20 m × 20 m plot that was established within each stand before soil sampling and site characterization. Basal area was estimated using tree inventory and diameter at breast height for 10 circular (1.5 m diameter) microplots randomly distributed within the experimental unit. Slope grade and aspect were estimated visually.

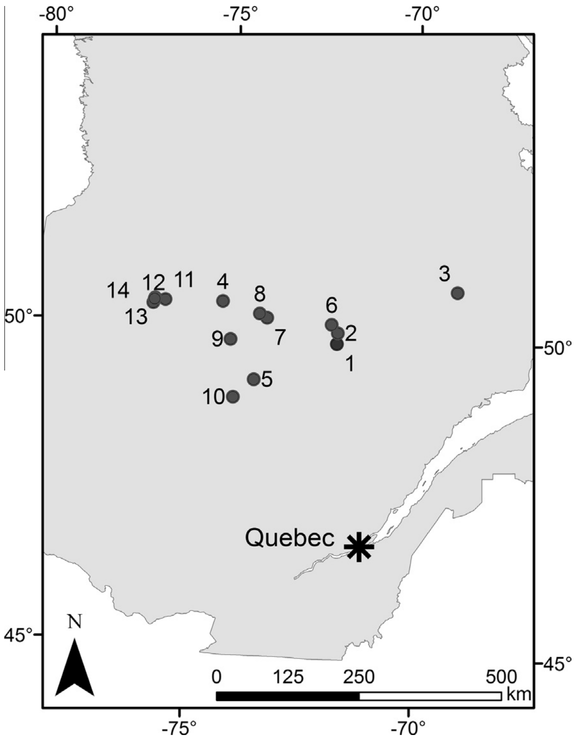

Fig. 1. Location of study sites. Identification numbers refer to those presented in Table 1.

2.2. Sampling and analysis of organic and mineral soil horizons

Soils were sampled during the summer of 2011. We sampled the entire organic horizon [i.e., L, F and H layers according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and O layer according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006)] and two fixed depth mineral soil horizons [i.e., surface mineral soil (0–15 cm depth) and subsurface mineral soil (15–40 cm depth)]. The surface mineral soil included the Ae horizon according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998), which corresponds with the E horizon of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). The subsurface mineral horizon included the Bf and Bhf horizons according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998), corresponding with Bs and Bhs horizons of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006).

Organic horizon sampling for bulk density, organic C, total N and pH analyses was done manually using a 25 cm × 25 cm wood frame and a shovel. The bulk density (in g cm^{-3}) of the organic horizon was calculated as the oven-dried (60 °C, 72 h) mass of the organic material recovered within the 25 cm × 25 cm wood frame divided by its volume. This procedure was done two times on arbitrarily selected samples within the experimental unit, and the average value of the two bulk density measurements was used for calculation and analysis. The thickness (in cm) of the organic horizon was calculated as the mean of 6–10 measurements taken randomly within a grid system of the experimental unit.