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Changes in soil chemical and biological properties after thinning and prescribed fire for ecosystem restoration in a Rocky Mountain Douglas-fir forest

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ABSTRACT

Practices such as thinning followed by prescribed burning, often termed 'ecosystem restoration practices', are being used in Rocky Mountain forests to prevent uncontrolled wildfire and restore forests to pre-settlement conditions. Prior to burning, surface fuels may be left or collected into piles, which may affect fire temperatures and attendant effects on the underlying soil. The objective of this study is to determine which pre-fire fuel management treatments best reduce fuel loadings without causing fire temperatures high enough to impair soil chemical and biological properties. Five fuel-management treatments were compared: large piles, small piles, cut and leave, slash-free areas around mature leave-trees, and unburned control. We measured key properties of forest floors and mineral soil (forest floor depth, soil pH, carbon and nutrient levels, and microbial abundances) prior to and during the first year after fire, and explored relationships among fuel loadings, fire temperatures and changes in these soil properties. Fire temperatures were above 300 °C for more than 3 h in the large-pile treatment but were lower and of shorter duration in the small-pile and cut-and-leave treatments. The most severe fire effects occurred around the leave-trees where temperatures were above 200 °C for more than 2 h, the forest floor was completely consumed, and the mature trees were killed. In the forest floors, abundances of all microbial groups were reduced and pH and availabilities of Ca^{2+}, Mg^{2+} and PO_4^{3-} were increased in all burned treatments. Forest floor C and N contents were reduced in burned plots by an average of 39% and 44% respectively, and availabilities of nitrate and sulphate were increased in the leave-tree areas only. There were few significant changes in mineral soil properties – pH and availabilities of NO_3^-, Mg^{2+} and SO_4^{2-} increased in leave-tree areas whilst PO_4^{3-} and K^+ increased under large piles. Microbial abundances had not recovered to pre-fire levels in any burned treatments after one year, which may be attributed to the persistence of significant increases in pH. Prior to the fire, microbial abundances were most closely related to N concentration in the forest floor, and C and N concentrations in the mineral soil; after fire, microbial abundances were most closely related to pH of the forest floor. Forest floor consumption and attendant changes in chemical and biological properties were most closely related to pre-fire moisture content, indicating that forest-floor moisture content may be as critical as fuel loading in determining impacts of prescribed fire on soil.

1. Introduction

Management of fuel loadings is critical for reducing the risk of large, uncontrolled wildfires in Rocky Mountain forest ecosystems (USDA-USDI, 2000; Schmidt et al., 2002). Fire suppression has caused increased forest fuel loadings and encroachment of small-diameter saplings into forest meadows or open stands, leading to more intense wildfires, higher rates of disease and transformations of wildlife habitat (Keane et al., 2002). In developed areas where wildland fire-use programs cannot be employed, the potential for extreme wildfires is being lowered through application of forest management practices which reduce stand density and fuel loadings (Fulé et al., 2001). Common techniques employed include mechanical thinning to reduce stand density, followed by prescribed fire to decrease the amount of surface fuels. Successful implementation of prescribed fire requires that fuels be managed such that flame lengths do not reach into mature-tree canopies (Graham et al., 2004). Fuel management options include pile-burning of leftover slash following thinning, broadcast-burning with slash in place, or both. All of these treatments result in the burning of compacted fuel near the soil surface, which increases temperatures in forest floors and soil, and may alter physical, chemical and biological properties of the soil.

Prescribed fire affects soil through consumption of the forest floor and heating of the soil, which are a function of fire temperature

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and duration. Between 2 and 37% of the forest floor mass is lost, on average, through consumption during prescribed fires (Covington and Sackett, 1984; Gundale et al., 2005). In the mineral soil, fire temperatures decrease with depth due to soil thermal conductivity (Campbell and Norman, 1998). Moist soils do not rise above 95 °C until all water has been driven off, but once this threshold is reached soil temperatures can rapidly rise to 200–300 °C (Franklin et al., 1997; Certini, 2005). Many biological mortality thresholds are reached at these temperatures, including those for seeds (50 °C), plant tissue (60 °C), fungi (100 °C) and bacteria (110 °C) (Hare, 1961; Dunn et al., 1979; Busse et al., 2005; Neary et al., 2005). Temperatures above 200 °C can volatilize nitrogen; temperatures greater than 760 °C are needed to volatilize other potentially limiting forest nutrients (Neary et al., 1999).

A recent meta-analysis of fire effects of soil C and N storage (Nave et al., 2011) indicated that prescribed fires have little effect on mineral soil, causing no significant changes in concentrations or pool sizes of C and N. In forest floors, prescribed fire did not significantly affect C and N concentrations, but reduced C and N storage by 46% and 35%, respectively. Concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) are usually elevated after prescribed fire (Covington et al., 1991; Kaye and Hart, 1998; Gundale et al., 2005; Jiménez Esquilín et al., 2007). Soil available P has been reported to increase (Vázquez et al., 1993; Banning and Murphy, 2008), decrease (Kaye and Hart, 1998) or stay the same (Kaye and Hart, 1998, Andreu et al., 1996). Calcium and Mg^{2+} concentrations have been reported to increase (Pietikäinen and Fritze, 1995) or remain the same after fire (Andreu et al., 1996; Gundale et al., 2005). Increases in soil pH after forest fire are common (Pietikäinen and Fritze, 1993; Vázquez et al., 1993; Choromanska and DeLuca, 2002; Jiménez Esquilín et al., 2007), although small declines in pH have also been reported (Abril et al., 2005; Gundale et al., 2005).

Effects of fire on soil microbiological communities can be assessed by comparing the phospholipid fatty acid (PLFA) content of soils before and after fire. PLFA analysis measures the abundance of broad taxonomic groups of bacteria, fungi and actinomycetes in soil. In a native, wet sclerophyll forest in Queensland, Australia, Campbell et al. (2008) found significantly lower abundance of Gram-positive bacteria, Gram-negative bacteria and actinomycetes in soils that experienced fire every two years compared to sites with 4-year fire intervals. In *Pinus sylvestris* stands of central Finland, total PLFA abundance, as well as total bacteria and fungi and the ratio of fungi to bacterial PLFA, were significantly lower in the organic matter of a burned site 2 years after fire than in an unburned control site (Bååth et al., 1995). Díaz-Raviña et al. (2006) found that granitic and acid schist soils heated to 350 °C for 10 min under laboratory conditions had 24–40% less total PLFA abundance than unheated soils. In contrast, in forests of western Montana Gundale et al. (2005) found no significant differences in total PLFA abundance among treatments (control, thinned, prescribed fire, thinned + prescribed fire) immediately or three years after fire, and concluded that these forest management treatments had no long-lasting effects on soil microbial communities.

The aim of this study was to determine which fuel management treatment best served the purpose of reducing surface fuel loadings while minimizing negative impacts on soil properties in interior Douglas-fir forests of the Rocky Mountain trench. We measured fire temperatures, forest-floor depth and key soil properties (moisture content, C and N concentrations, pH, nutrient availability and microbial community composition (PLFA) in four fuel-management treatments and in an unburned control prior to and 10 days, 3 months and 1 year after a prescribed fire. Relationships among fuel loadings, fire temperatures and soil properties were explored, as were relationships between soil properties and microbial communities. Based on studies to date, we hypothesized that:

1. Changes in soil chemical and biological properties will be greatest in treatments with the largest fuel loadings.
2. Soil pH and concentrations of inorganic N, Ca and Mg will increase while microbial abundances will decrease in burned plots, especially in those with the highest fire temperatures.
3. Changes in soil biological and chemical properties will be sustained for at least one year following the prescribed fire.

2. Methods

2.1. Site description

The study site is located in the Rocky Mountain Trench of southeast British Columbia (BC) (49° 43′ 10 N and 115° 38′ 35 W, elev. 1000 m, 7–12% slope), approximately 20 km northeast of Cranbrook, BC. It is positioned on a geographic bench above the valley bottom with surrounding mountains that rise to 2500 m. The site is classified as Interior Douglas-fir Dry Mild (IDFdm2/04) under the BC Biogeoclimatic Ecosystem Classification (Pojar et al., 1986). IDF forests encompass about 5.5% of BC's land area. The adjacent valley bottom has a mean annual precipitation of 32 cm, with 30% in the form of snow (National Climate Data and Information Archive, xxxx). Annual monthly mean high and low temperatures averages are 11.4 °C and −0.37 °C, respectively. *Pseudotsuga menziesii* var. *glauca* (interior Douglas-fir) and *Larix occidentalis* (western larch) are the dominant tree species, while shrub species include *Spiraea betulifolia* (birch-leaved spirea), *Arctostaphylos uva-ursi* (kinnikinnick) *Rubus idaeus* (raspberry) and *Rosa acicularis* (prickly rose). The herb layer after thinning is dominated by *Calamagrostis rubescens* (pinegrass). The modal soil is classified as Orthic Eutric Brunisol (Soil Classification Working Group, 1998) and is less than 1 m deep. It is a well-drained, sandy loam with 30–50% coarse fragments and is non-effervescent (10% HCl) until immediately above the calcareous bedrock. Averaged forest-floor depth before fire was 4.6 cm.

A variety of silvicultural treatments were implemented by the BC Ministry of Forests and Range in this area during the previous 5 years. The largest treatment unit (TU2 – 20 ha) had been commercially thinned in 2004; all trees >30 cm were retained for residual density of 150 trees ha^{-1}. Slash was piled into small (~1 m^3) and large (~4 m^3) piles in 2008. An adjacent unit, TU5 (9 ha), was a cut-and-leave thinning treatment established in 2008, where all trees less than 30 cm were felled in the same direction and left on site. The remaining mature trees in TU5 had relatively deep forest floors (>6 cm) but small amounts of woody materials beneath them. Areas outside these TUs and the prescribed fire perimeter had low surface-fuel loadings and abundant saplings. The entire study area was 330 ha, and all plots were within 1 km of one another.

2.2. Experimental design

Fifteen plots, each of 1.25-m radius, were non-randomly placed within five different fuel management treatments within the two treatment units (TU2 and TU5). Three "large pile" plots were under slash piles about 2 m high and 2 m in diameter in TU2 (these could also be classified as "hand" piles); three "small pile" plots were under slash piles about 1 m high and 1 m in diameter in TU2; three "cut and leave" plots were under felled small trees in TU5 which had been cut in 2008 and retained red needles; three "leave-tree" plots were directly beneath remaining mature trees in TU5 with no downed wood within 3–5 m of the tree bole; and three "unburned control" plots were located just outside of the treatment units and fire perimeter.