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Legacy effects of prescribed fire season and frequency on soil properties in a *Pinus resinosa* forest in northern Minnesota

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ABSTRACT

Prescribed fire is a widely used ecosystem management approach and the vast majority of burns are conducted during the dormant season; however, these burning conditions (and therefore the type and persistence of fire effects) often differ from those of natural or historical fire regimes. Therefore, we leveraged a historical study (conducted 1959–70) with remeasurements in 2015 to evaluate effects of fire season (dormant, summer), frequency (annual, biennial, periodic), and their interaction on soil physical and chemical properties in a red pine (*Pinus resinosa* Ait.) forest in northern Minnesota, USA. To protect against across-year differences in sampling and analysis, we used a meta-analysis approach to evaluate treatment effects on soil properties. We also used non-metric multidimensional scaling (NMDS) ordination to investigate legacy (> 45 years post-fire) treatment effects.

The greatest effects of fire occurred in organic horizons, and decreased with depth. In the short-term, fire decreased organic horizon depths and nitrogen (N) and increased base cations (K, Ca, Mg) and pH in the mineral soil, whereas effects on phosphorus (P) were variable. Prescribed fire treatments had legacy effects on organic horizon and mineral soil properties > 45 years post-fire. In general, summer burns decreased nutrient stocks, whereas dormant season burns increased nutrient stocks, and the majority of legacy effects occurred in annual burn treatments, in both seasons. Legacy effects of summer burns decreased organic horizon depths, organic matter, nutrient stocks (N, P, K), and pH, as well as lower (0–15 cm) mineral soil N; whereas, the dormant annual burn increased Ca in the total forest floor and N and P in the upper (15–91 cm) mineral soil. In contrast, the summer annual burn increased P, whereas the dormant annual burn decreased pH in the lower mineral soil. Trends in short- and long-term effect sizes appeared to differ by season of burning and further magnified by increased fire frequency within season. Relative to dormant season burns, summer burns resulted in immediate and long-lasting desirable effects for red pine ecosystems (e.g., decreased forest floor depths and nutrient stocks) without persistent undesirable effects (e.g., increased nutrient stocks or changes in cation exchange capacity, soil texture, and bulk density) in the mineral soil. Our results suggest that summer burns may be a valuable approach to increase the variability in burn schedules representative of historical regional fire regimes in red pine forests, and may help promote soil characteristics that support overall ecosystem health.

1. Introduction

Forest soils respond to changes in fire regime. Fire regimes, characterized by local spatial and temporal patterns and effects on ecosystems, have been altered by decades of prolonged fire suppression policies as well as contemporary use of prescribed fire that may have legacy effects on soil properties (Brown and Smith, 2000; Foster et al., 2003; Krebs et al., 2010). Historically, regional fire regimes were responsible for maintaining forest structure, species composition, and soil nutrient dynamics (Van Wagner, 1970; Ryan et al., 2013). Red pine (*Pinus resinosa* Ait.) forests of the Lake States region are an example of an ecosystem type that has developed on well-drained, nutrient-poor, sandy soils with a fire regime of low to mixed severity surface fires (Drobyshev et al., 2008) occurring with an irregular return frequency of approximately 30 years (Bergeron and Brisson, 1990). Historically, these fires occurred during dormant (i.e., spring or fall) and summer seasons, and were associated with localized drought events and human activity (Heinselman, 1973; Guyette et al., 2016). Fires encouraged red pine establishment and regeneration by reducing overstory canopy density and understory competition as well as by preparing mineral

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seedbeds by combusting forest floor organic matter (Van Wagner, 1970). Similar to other fire-dependent ecosystems, red pine forests have experienced significant alterations in fire regimes that have resulted in shifts in species composition, mesophication (Nowacki and Abrams, 2008), structurally simplified stands, excess accumulation of fuels, and decreased natural regeneration (Frelich, 1995; Cleland et al., 2004). Prescribed fire is a management tool that may be used to mitigate the effects of prolonged wildland fire suppression and is being increasingly implemented at local and national levels to restore fire to fire-dependent ecosystems (Ryan et al., 2013). Dormant season prescribed fires are commonly implemented due to the weather, operational, and safety constraints associated with summer season prescribed fires (Quinn-Davidson and Varner, 2012; Melvin, 2015). Yet, contemporary implementation of infrequent dormant season prescribed fires in the Lakes States region may not reflect historical regional variability of wildland fire season, frequency, and intensity (Van Wagner, 1968; Heinselman, 1973; Dickmann, 1993). The effects of contrasting seasons and frequencies of prescribed fire on soils and ecosystem trajectories are poorly understood, yet are required to elucidate local responses of fire-adapted communities.

Fire influences physical, chemical, and biological properties of soils. Losses and additions of nutrients to the soil are a common effect of fire, and are closely associated with fire intensity (i.e., energy released) (Neary et al., 2005). For example, soil organic matter and nitrogen are volatilized at relatively low temperatures (200–450 °C), whereas phosphorous and base cations (potassium, calcium, magnesium) require much higher temperatures (770–1240 °C) to volatilize (Neary et al., 2005). Nutrients may be lost via volatilization into the atmosphere, transported off-site by erosion, or remain *in situ* as post-fire ash deposits and immobilized by soil microorganisms and vegetation or translocated into the mineral soil profile (DeBano, 2000; Certini, 2005). Soil temperature during fire depends in part on fire intensity and may vary widely within and across season and frequency of prescribed fires (Keeley, 2009; Wittenberg, 2012). For example, seasonal dissimilarities may be driven by differences in fuel moisture, with summer fires often characterized by higher fire intensities than dormant season conditions (Govender et al., 2006), whereas increased frequency of fire within season may magnify seasonal effects of fire (Busse et al., 2014). Thus, the season as well as the number of burns conducted both have potential to influence ecosystem responses to fire.

The season and frequency of prescribed fire in red pine forests have direct and indirect effects on overstory and understory vegetation community composition and structure (Buckman, 1964; Henning and Dickmann, 1996; Weyenberg and Pavlovic, 2014; Scherer et al., 2016). Immediate and persistent responses of vegetation to fire can affect soil properties and nutrient dynamics by mitigating losses through erosion and leaching, accelerating nutrient recovery via litterfall inputs and atmospheric nitrogen fixation, and influencing belowground interactions among plants, microbes, and soil (Tappeiner and Alm, 1975; Staddon et al., 1997; Zeleznik and Dickmann, 2004).

Short-term (< 10 years) responses of soil to fire are well-studied, and general trends include decreases in organic horizon depths, volatilization of nitrogen, and increases in pH and base cations, whereas phosphorous responses are variable (Certini, 2005; Neary et al., 2005). However, there is a lack of data on long-term effects of fire on soils in general, and in particular, in red pine forests of the Lake States region. For example, a review of fire effects on soils in the Lakes States region revealed that only 8% of the studies were conducted in mixed pine or red pine forests and that 70% of the reported data from measurements were taken < 10 years after a fire event (Miesel et al., 2012).

Despite the ecological and economic value of red pine forests, there remains an absence of long-term studies regarding the use of prescribed fire to maintain regional fire-dependent ecosystems, and its influence on soil properties. An early study in a naturally-regenerated red pine forest in northern Minnesota investigated the effects of prescribed fire on site productivity, understory competition, and soil properties (Buckman, 1964; Alban, 1977). The *Red Pine Prescribed Burning Experiment* study began in 1959 with treatments and measurements through 1970. Alban (1977) concluded from a single year of measurements collected in 1969 that ten years of prescribed fire decreased understory competition and nutrients in the forest floor horizon, whereas nutrients in the mineral soil increased, without affecting site productivity. We leveraged the historical study site and initial raw datasets collected from 1959 to 1969, including the 1969 measurements previously reported by Alban (1977), with remeasurements in 2015 to: (1) evaluate short-term and intermediate trends over > 10 years (1959–1969) as well as cumulative effects of prescribed fire treatments on soil responses across years (1959–2015) for which data were available; and (2) determine long-term soil responses and changes over time to prescribed fire treatments > 45 years post-fire. We hypothesized that (1) summer prescribed fire treatments would result in the greatest magnitude in cumulative effect sizes on soil properties across years and (2) differences among fire treatments in organic and mineral soil properties would persist > 45 years since the last prescribed fire. Our rationale for the first hypothesis was that summer burns are associated with lower fuel moistures and greater fire intensity; therefore greater combustion of soil organic horizons would result in greater losses and/or redistribution of nutrients in organic and mineral soil horizons relative to dormant season burns. Our second hypothesis was based on the rationale that direct effects of fire on soil properties as well as the indirect effects of post-fire vegetation recovery and nutrient cycling over time would combine to influence persistent differences in soil properties among fire treatments.

2. Methods

2.1. Study area

Our study site utilized the *Red Pine Prescribed Burning Experiment* located on the Cutfoot Experimental Forest (CEF) in the Chippewa National Forest, in Itasca County in northern Minnesota, USA (latitude 47°40′N, longitude 94°5′W) and is further described in Buckman (1964). The CEF is administered by the U.S. Forest Service Northern Research Station (Grand Rapids, MN). The study area is characterized by a continental climate with humid (80% relative humidity) summers exceeding temperatures of 32 °C and winter minimum temperatures below −35 °C (U.S. Forest Service, 2009). The growing season length is 100–120 days. Average annual precipitation ranges from 500 to 640 mm of rainfall with average winter snowfall depths between 1 and 2 m, and summer droughts are common (U.S. Forest Service, 2009).

The forest community is dominated by red pine interspersed with jack pine (*Pinus banksiana* Lamb.), eastern white pine (*Pinus strobus* L.), paper birch (*Betula papyrifera* Marsh.), and quaking aspen (*Populous tremuloides* Michx.) (U.S. Forest Service, 2009). The forest at our study site originated naturally following a high severity fire in 1870, and fire scars indicate several major fires occurred in the mid to late 19th century (U.S. Forest Service, 2009). Measurements taken in 1959 prior to initiation of the original study indicated overstory trees were 90-year-old red pine with an average of 30.7 cm dbh (diameter at breast height, 1.37 m). The site index for red pine was 15.2 m at 50 years. The dominant understory species include hazel (*Corylus* spp.) and alder (*Alnus* spp.). Fire suppression resulted in abundant hazel in the understory and several studies investigated the effects of prescribed fire to reduce hazel density and promote natural red pine regeneration (Buckman, 1964; Alban, 1977). Management history indicates few silvicultural treatments were applied on the site. The study site was thinned in the winter of 1959 to an overstory basal area of 27–29 $m^2\,ha^{-1}$ to create a uniform tree density (Alban, 1977). The slash was removed from the burn treatment compartments to minimize fuel loading, site variability, and prescribed fire-induced tree mortality. No additional overstory management has been performed since the initial thinning.