Forest Ecology and Management 415–416 (2018) 47–57

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

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

Joshua A. James[a,*], Christel C. Kern[b], Jessica R. Miesel[a]

[a] Department of Forestry, Michigan State University, East Lansing, MI 48824, USA
[b] USDA Forest Service, Northern Research Station, Rhinelander, WI 54501, USA

ARTICLE INFO

*Keywords:*
Fire effects
Forest floor
Mineral soil
Remeasurement
Meta-analysis
Long-term

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

* Corresponding author at: 480 Wilson Road, East Lansing, MI 48824, USA.
*E-mail addresses:* jamesjo6@msu.edu (J.A. James), mieselje@msu.edu (J.R. Miesel).

https://doi.org/10.1016/j.foreco.2018.01.021
Received 4 October 2017; Received in revised form 10 January 2018; Accepted 13 January 2018
Available online 23 February 2018
0378-1127/ 

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.

The study area soil belongs to the Eagleview soil series, a mixed, frigid, Lamellic Udipsamment formed in glacial outwash parent material from the Late Wisconsin Age (NRCS, 2017). The soil is deep and well-drained with a medium to fine sand texture on 1–8% slopes typical of red pine forests of northern Minnesota. Prior to initiating the burning experiments in 1960, Alban (1977) described the soil as weakly developed with the forest floor approximately 8 cm thick and underlying mineral soil consisted of loamy sand including A (0–1 cm), E (1–11 cm), and B (11–47 cm) horizons. Stratified sands and gravels interspersed with thin lenses of very fine sandy loam were measured below the B horizon and calcium carbonate occurred intermittently below 127 cm.

### 2.2. Experimental design and treatments

Prescribed fire treatments representing contrasting fire seasons and frequencies were implemented within 0.4 ha compartments assigned using a randomized complete block design, with seven treatments replicated in each of four experimental blocks. The 28 compartments were each surrounded by a fire exclusion perimeter and contained a 0.08 ha circular plot. A total of seven prescribed fire treatments were randomly assigned to compartments within blocks and were implemented from spring 1960 through the summer of 1970 to test the effects of fire season, frequency, and their interaction on soil physical and chemical properties. The seasonality of fire was categorized as either dormant or summer, with dormant season burns conducted in the absence of leaves on trees and shrubs (i.e., spring or fall), whereas summer burns were applied from late June through mid-August when vegetation assumed full physiological activity. The frequency of treatments was categorized as annual (every calendar year), biennial (every other calendar year), and periodic (every 6–9 years). The seven treatments administered included: dormant annual (DA), dormant biennial (DB), dormant periodic (DP), summer annual (SA), summer biennial (SB), summer periodic (SP), and an unburned control (CC) for reference conditions (Table 1).

Prescribed burns were conducted 5–15 days following a rain event (Buckman, 1964; Alban, 1977). This resulted in forest floor horizon moisture content averaging approximately 100% of dry weight in dormant season burns and 40% in summer season burns (Alban, 1977). Pre-burn preparation included constructing fire lines to mineral soil around each compartment, felling snags, and removing high risk dead and down woody fuels near fire lines. Backing fires were used to initiate burns within each compartment. Strip headfires followed varying from 3 to 6 m in width. Fires were of low to moderate intensities with < 1 m flame heights and resulted in minimal overstory tree damage.

Alban (1977) reported that burning led to the complete combustion of the litter horizon for all burn treatments and of the fermentation horizon for annual and biennial frequencies for both summer and dormant season burns in 1969. The summer annual burn decreased organic matter by approximately 50% and in some circumstances resulted in the complete combustion of the forest floor horizon, exposing mineral soil in < 5% of the burned compartments (Alban, 1977). The last prescribed burn in 1970 resulted in a total of 10–11 burns in the annual treatments, five burns in the biennial treatments, and two burns in the periodic treatments (Table 1). No additional prescribed fire treatments or changes to the experimental units have been performed since the summer of 1970.

### 2.3. Field methods

In June 2015 we re-sampled the original research plots and collected organic and mineral soil samples. The initial (1959–1969) soil samples were collected along a NE (45°) to SW (225°) transect bisecting the plot origin; however, all available sampling increments along these transects had been previously sampled. We therefore followed the original authors' instructions to establish a new sampling transect, which we established along an adjusted NE (22.5°) to SW (202.5°) azimuth.

We collected organic horizon and mineral soil samples at 3.05 m from the plot origin along each corresponding azimuth within each of the 28 plots, for a total of 56 subsampling points. We placed a 30 cm diameter circular frame at each subsampling point to measure organic soil horizons (litter ($O_i$), fermentation ($O_e$), and humus ($O_a$)). Forest floor horizon depth was taken at each of three locations along the circumference of the circular frame. Four locations were used if any anomalies occurred (i.e., tree roots, rocks). We used a serrated gardening knife to cut around the inside circumference of the circular frame before collecting each of the three organic horizons from within the frame. Cones, bark, and woody debris were included as part of the organic horizons, whereas we omitted woody material > 0.64 cm diameter. All organic horizon samples were returned to the laboratory and dried at 60 °C to constant mass prior to chemical analysis.

After we removed the organic horizons, we then collected mineral soil samples by depth within the circular frame. Two different sets of depth increments had previously been used for the study. We adopted the most recent set of depth increments: 0–10.16 cm, 10.16–50.80 cm, and 50.80–99.06 cm (Alban, 1977). The 0–10.16 cm increment was collected using a slide hammer with attached cup and sleeve, the 10.16–50.80 cm increment was collected using a t-handle soil probe, and the 50.80–99.06 cm increment was collected using a slide hammer with attached soil probe. Mineral soil samples were returned to the laboratory and dried at 60 °C to constant mass prior to chemical analysis.

### 2.4. Laboratory analysis

For our 2015 soil samples, we followed the soil chemical analysis methods used by Alban (1977) to the greatest extent possible. Organic soil horizon nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), pH, depth, mass, organic matter (OM), ash content, and bulk density were measured along with mineral soil N, P, K, Ca, Mg, pH, cation exchange capacity (CEC), soil texture, and bulk density. We weighed each organic soil horizon after all living material (i.e., plants, roots, lichens, moss, insects, worms, etc.) as well as large

**Table 1**
Description of prescribed fire treatments implemented in the original *Red Pine Prescribed Burning Experiment* (1959–1970) in the Cutfoot Experimental Forest, Minnesota, USA. Prescribed fire treatments are shown by season, frequency, interaction of season and frequency, burn dates, and number of times burned, for n = 4 replicates per treatment and control. Discrepancies in scheduled burn dates and implementation of treatments were a result of unfavorable burning conditions.

| Season | Frequency | Treatment | Burn dates (month/year) | Number of times burned |
|---|---|---|---|---|
| Control | Control | CC | – | 0 |
| Dormant | Annual | DA | 5/1960, 5/1961, 5/1962, 4/1963, 5/1964, 10/1964, 5/1966, 5/1967, 5/1969, 5/1970 | 10 |
| | Biennial | DB | 5/1960, 5/1962, 5/1964, 5/1966, 5/1969 | 5 |
| | Periodic | DP | 5/1960, 5/1969 | 2 |
| Summer | Annual | SA | 8/1960, 6/1961, 8/1962, 6/1963, 6/1964, 7/1965, 8/1966, 7/1967, 7/1968, 8/1969, 7/1970 | 11 |
| | Biennial | SB | 7/1960, 8/1962, 6/1964, 8/1966, 7/1968 | 5 |
| | Periodic | SP | 7/1960, 7/1967 | 2 |

rocks and scat were removed and discarded. Bulk density was calculated for each organic horizon as a mass per volume ratio (g $cm^{-3}$). The corresponding samples within plot were composited into one soil sample per plot prior to grinding. Each organic horizon was ground to pass a 1 mm screen. Organic horizons were analyzed using the following methods: N by Kjeldahl (Bremner, 1965), and P, K, Ca, and Mg by ashing in a muffle furnace at 525 °C for 4 h followed by uptake in 3 N HCl. P was determined colorimetrically (Alban, 1972), whereas K, Ca, and Mg were determined by atomic absorption (PerkinElmer AAnalyst 400). We measured pH in a 4:1 water to volume ratio (LabFit AS-3000). Organic matter and ash content were determined from the loss on ignition at 525 °C for 4 h. In addition, we used elemental analysis (Costech, Italy, combustion temperature 1000 °C) to quantify total nitrogen and compare to Kjeldahl nitrogen.

We removed all visible organic material from mineral soil samples. We then sieved each mineral soil sample through a 2 mm screen and composited the fine fraction within each increment into one soil sample per plot for chemical analysis. Mineral soils were analyzed using the following methods: N by Kjeldahl, P was extracted using 0.01 N HCl, whereas K, Ca, and Mg were extracted using 1 N neutral ammonium acetate and determined as described above. We measured pH using a 1:1 water to volume ratio. CEC was calculated using pH buffer. Soil texture by particle size distribution was analyzed by hydrometer (Day 1965). Bulk density was calculated as a mass per volume ratio (g $cm^{-3}$).

### 2.5. Statistical analysis

We used a meta-analysis approach to estimate the effect size of prescribed fire treatments on soil properties across years using historical raw plot-level sample data collected from 1959 to 1969, including Alban's (1977) 1969 measurements, along with our new remeasurement data collected in 2015. For this approach, we considered individual years as similar to an individual study, and we calculated standardized treatment effects relative to the control treatment within year. This approach protects for across-year differences in soil sampling or analysis methods. For example, although we followed the original field and laboratory methods to the greatest extent possible, identifying boundaries between organic soil horizons was somewhat subjective. Furthermore, the historical sampling events used two different sets of depth increments for sampling mineral soil (i.e., increments of 0–15.24 cm, and 15.24–91.44 cm were used in years prior to 1969, whereas increments of 0–10.16 cm, 10.16–50.80 cm, and 50.80–99.06 cm were used in 1969 and 2015). We therefore assigned the pre-1969 mineral soil increment depths across all years and calculated the weighted mean and weighted standard deviation for each upper (0–15.24 cm) and lower (15.24–91.44 cm) mineral soil increments. Differences in laboratory procedures and conditions between the historical and 2015 measurements may also affect measured responses. Lastly, the historical data measured between 1959 and 1969 included reports of some nutrients in parts per million (ppm) with insufficient information to determine whether the ppm was reported on a solution basis or soil mass basis. We performed the meta-analysis of soil responses to prescribed fire treatments using MetaWin 2.0 (Rosenberg et al., 2000). The natural log-transformed response ratio was used to estimate treatment effect size (ES) (Hedges et al., 1999):

$$\mathrm{ES} = \ln(\mathrm{R}) = \ln(\overline{\mathrm{X}}_{\mathrm{T}}) - \ln(\overline{\mathrm{X}}_{\mathrm{C}}) \tag{1}$$

where $\overline{X}_T$ is the mean soil response of the prescribed fire treatment within soil horizon and year and $\overline{X}_C$ is the mean soil response of the control within soil horizon and year (n = 4). The effect size is a standardized unitless metric that allows comparison among soil response variables reported in different units across years. The variance, v, of the effect size was calculated as:

$$v_{ES} = \frac{(\mathrm{SD_T})^2}{\mathrm{n_T}\overline{\mathrm{X}}_{\mathrm{T}}^2} + \frac{(\mathrm{SD_C})^2}{\mathrm{n_C}\overline{\mathrm{X}}_{\mathrm{C}}^2} \tag{2}$$

where $SD_T$ and $SD_C$ is the standard deviation and $n_t$ and $n_c$ is the number of replicates of the prescribed fire treatments and control, respectively, within soil horizon and year. The 90% confidence interval (CI), $100(1-\alpha/2)\%$ around ES was used due to the high variability in studies of soils and calculated as:

$$\mathrm{CI} = \mathrm{ES} \pm Z_{\alpha/2}\sqrt{v} \tag{3}$$

where $Z$ is the $Z$-score and $\alpha$ is the Type 1 error (0.10). The cumulative effect size ($\overline{ES}$) of prescribed fire treatments was determined for each soil variable within soil horizon across all years (1959–1969, and 2015) as:

$$\overline{ES} = \frac{\sum_{i=1}^{n} w_i E_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where the weight of the $i^{th}$ study is the reciprocal of the sampling variance $w_i = 1/v_{ES}$, n was the number of years for which measurements existed, and $E_i$ is the effect size for the $i^{th}$ study. The cumulative effect size variance was calculated as:

$$s^2_{\overline{ES}} = \frac{1}{\sum_{i=1}^{n} w_i} \tag{5}$$

The 90% confidence interval of the cumulative effect size was determined as:

$$\mathrm{CI} = \overline{\mathrm{ES}} \pm t_{\alpha/2(\mathrm{n}-1)} \times s^2_{\overline{ES}} \tag{6}$$

where $t$ is the value from the Student's $t$-distribution and $\alpha$ is the Type 1 error (0.10). We were unable to calculate a robust analysis of standardized effect sizes for upper and lower mineral soil CEC, texture, and bulk density using the historical study (1959–1969) due to insufficient data. In addition, we used non-metric multidimensional scaling (NMDS) to investigate treatment effects on overall soil properties and changes over time (1969–2015) using the standardized effect sizes (ES) calculated in the meta-analysis approach as inputs for the ordination. We performed the NMDS using PC-ORD Version 7 (McCune and Mefford, 2015) with Euclidean distance measure in the slow and thorough mode with a maximum of 500 iterations. Kendall rank correlation coefficients ($\tau$) were calculated for correlations between individual soil response variables and NMDS axes, with statistical significance determined at the $\alpha = 0.10$ level.

Remeasurements in 2015 indicated there were no effects of fire treatments or time since the last prescribed fire on mineral soil CEC, texture, and bulk density. Therefore, these data are not included in the results presented here; however, we report supplementary data that provides descriptive statistics for all soil properties measured in 2015 (> 45 years post-fire) on a mass per unit area basis, along with results of analysis of variance (ANOVA) used to evaluate the effects of fire season and frequency on soil properties (Appendix A).

## 3. Results

### 3.1. Individual and cumulative soil responses to prescribed fire

Prescribed fire treatments affected some, but not all, soil properties. In particular, litter and fermentation depths decreased across all treatments during the time period of the study that involved active burning (1960–1970) and returned to near original depths by 2015 (> 45 years post-fire) (Fig. 1a and b). However, the summer annual burn resulted in a persistent decrease in litter and humus horizon depths measured > 45 years after the last fire treatments (Fig. 1a and c). Total forest floor depth and organic matter content decreased during active burning years for annual and biennial frequencies, regardless of season (Fig. 1d and e). The summer annual burn was the only treatment

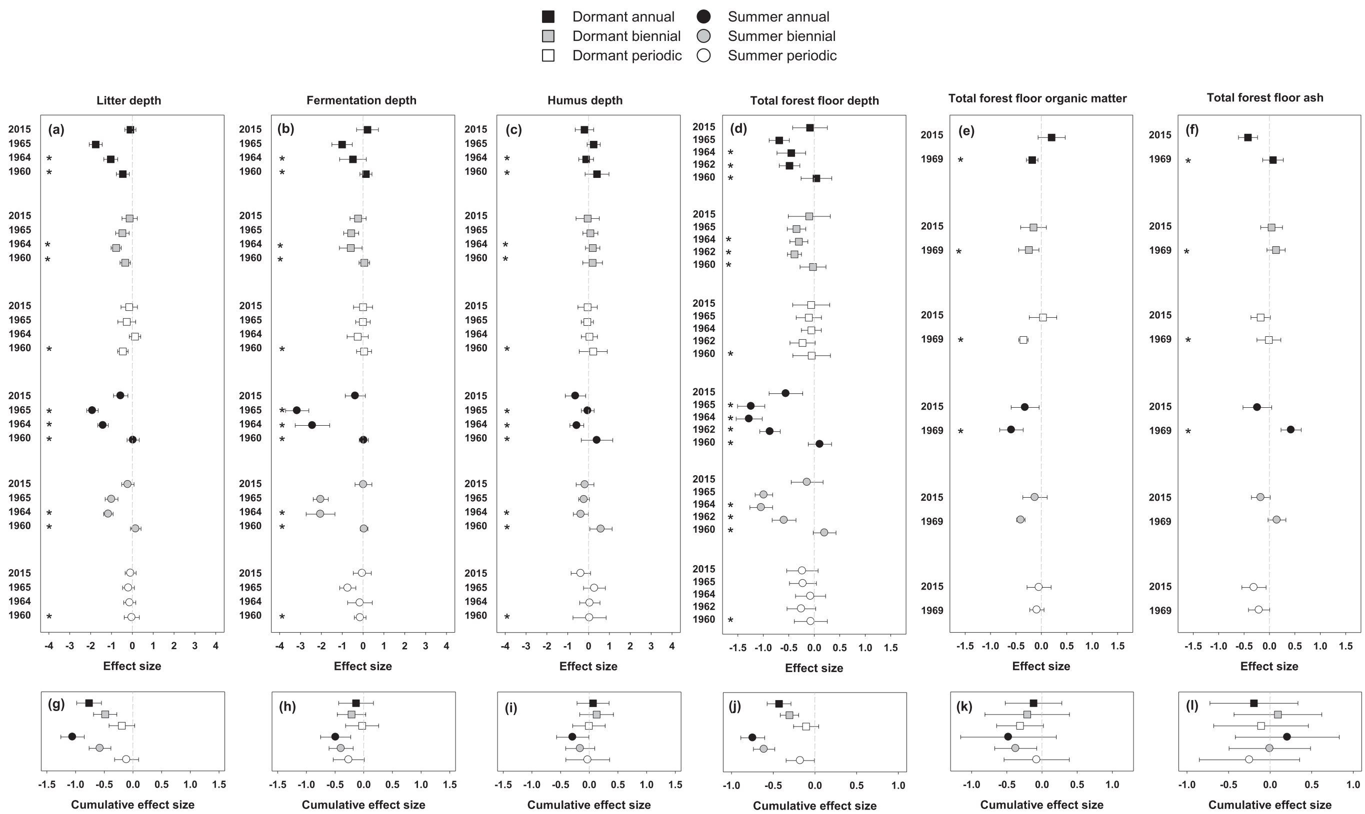


**Fig. 1.** Standardized effect sizes ( ± 90% confidence intervals) for organic horizon litter, fermentation, humus, and total forest floor (litter, fermentation, humus) depth and total forest floor organic matter and ash content. Within-year effect sizes are shown in upper panels, and cumulative effect sizes (across all years) are shown in lower panels. Symbol shape represents prescribed fire season, whereas shading represents frequency, for n = 4 replicates per treatment. Asterisks [*] in upper panels indicate the years in which prescribed fire treatments were conducted. Error bars that do not overlap the 0 effect size indicate a statistically significant treatment effect relative to the control, and non-overlapping error bars indicate statistically significant differences among treatments ($\alpha$ = 0.10). Note changes in x-axis scaling between panels.

for which depth and OM decrease persisted to 2015 (Fig. 1d and e), whereas a decrease in ash content persisted in both dormant annual and summer periodic treatments (Fig. 1f). Across all years (1959–2015), the cumulative effect size in the litter layer showed the most pronounced loss of depth, and the magnitude of effect increased with increased fire frequency (Fig. 1g); these patterns were also evident in the total forest floor depth (Fig. 1j). We observed a trend toward increased OM content with increased fire frequency in dormant season treatments, but a decrease in OM with increased fire frequency in summer treatments; a similar inverse trend between seasons was observed for ash content (Fig. 1k and l).

For the active burning years (1960–1970), summer annual and biennial burn treatments decreased total forest floor N and K, whereas P increased (Fig. 2a–c). We observed persistent decreases in 2015 (> 45 years post-fire) for N in the summer biennial treatment, and for P and K in summer annual and periodic treatments (Fig. 2a–c). During active burning years, total forest floor Ca decreased, whereas pH increased with increased fire frequency regardless of season (Fig. 2d and f). However, effects on cations and pH that persisted in 2015 were limited only to the dormant annual burn (increased Ca) and summer periodic burn (decreased pH) (Fig. 2d and f). Across all years (1959–2015), the summer annual burn increased P, however, summer biennial and periodic burns decreased P and K (Fig. 2h and i). Increased summer season fire frequency decreased Ca and Mg, however, increased dormant season fire frequency increased Ca and Mg (Fig. 2j and 2k). In contrast, pH increased with increased fire frequency regardless of burn season (Fig. 2l).

We observed no effects of treatments on upper mineral soil N and K during active burning years (1960–1970), and effects on P were variable (Fig. 3a and b). However, the dormant annual burn resulted in a persistent increase in N and P, measured in 2015 (> 45 years post-fire) (Fig. 3a and b). Summer and dormant season burns increased upper mineral soil Ca and Mg during active burn years (Fig. 3d and e). All treatments showed a slight increase in pH during active burn years, and a decrease measured in 2015 (Fig. 3f). The cumulative effects in upper mineral soil across all years (1959–2015) indicated that N decreased with increased fire frequency, regardless of burn season (Fig. 3g), whereas the effect of summer burns increased P with increased fire frequency and the effects of dormant season burns varied across frequencies (Fig. 3h). Upper mineral soil K increased in the dormant biennial treatment and showed a trend towards a decrease with increased summer season fire frequency (Fig. 3i). Upper mineral soil Ca showed a significant increase in the periodic burn frequency for both summer and dormant season fires, and in the dormant biennial treatment (3j). Although the cumulative effect size of the dormant annual treatment was not statistically significant, all dormant season burn frequencies suggest a trend toward increases in Ca relative to the control, with the magnitude of increase inverse to burn frequency (3j). Upper mineral soil pH increased in the dormant biennial and summer annual burns, but decreased in the dormant annual burn (Fig. 3l).

Lower mineral soil N decreased during active burning (1960–1970) across all treatments, excluding the summer annual burn, however, the summer annual burn resulted in a persistent decrease in N measured in 2015 (> 45 years post-fire) (Fig. 4a). In contrast, P increased across active burning years for biennial and periodic burns, regardless of season, and the summer annual burn increased P measured in 2015 (Fig. 4b). Ca and Mg increased during active burning across all treatments, excluding the dormant annual burn (Fig. 4d and e). pH increased across all treatments measured in year 1962 and a decrease in pH persisted for the dormant annual burn in 2015 (Fig. 4f). There were few significant overall treatment effects across all years (1959–2015) for the lower mineral soil, except for summer annual (increased P and pH)

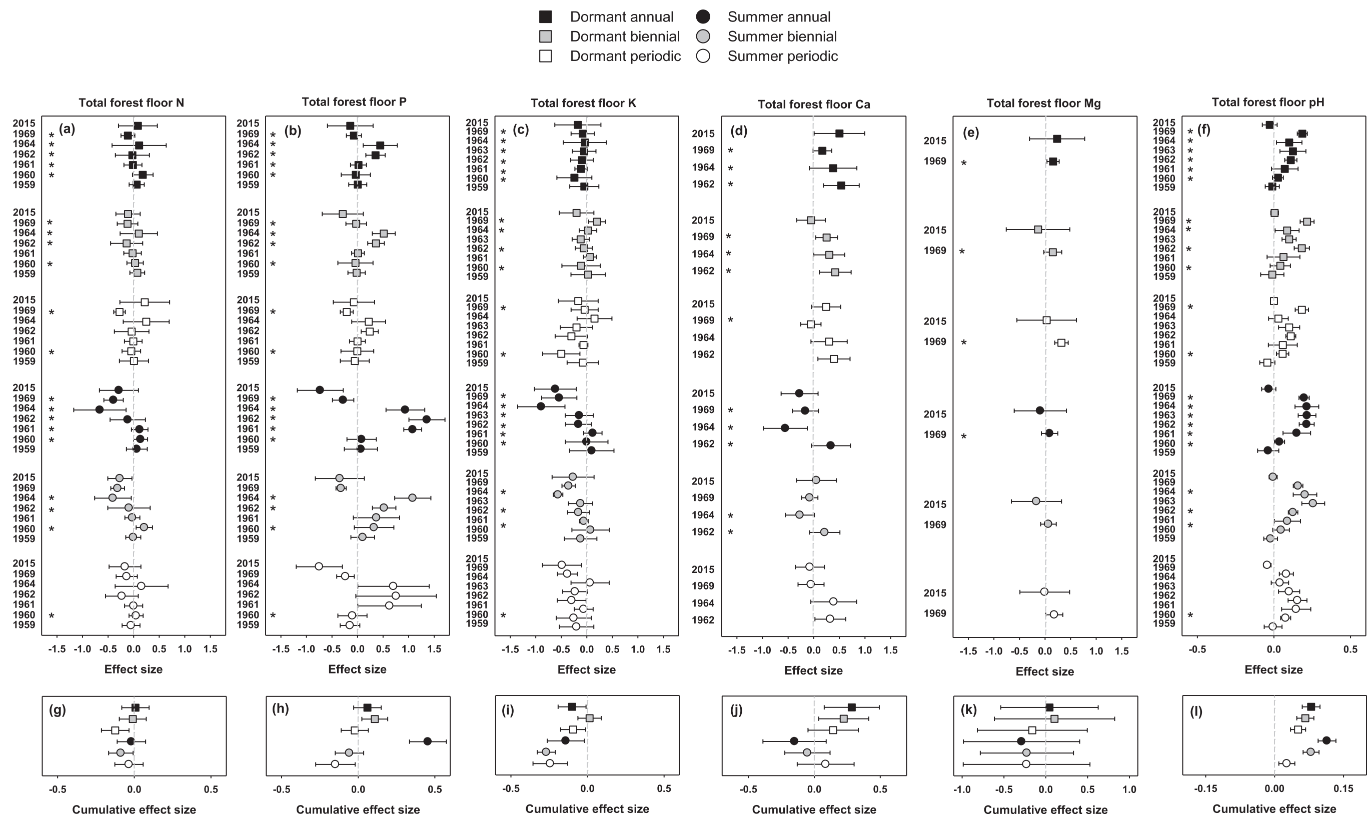


**Fig. 2.** Standardized effect sizes ( ± 90% confidence intervals) for total forest floor (litter, fermentation, humus) horizon N, P, K, Ca, Mg, and pH. Within-year effect sizes are shown in upper panels, and cumulative effect sizes (across all years) are shown in lower panels. Symbol shape represents prescribed fire season, whereas shading represents frequency, for n = 4 replicates per treatment. Asterisks [*] in upper panels indicate the years in which prescribed fire treatments were conducted. Error bars that do not overlap the 0 effect size indicate a statistically significant treatment effect relative to the control, and non-overlapping error bars indicate statistically significant differences among treatments ($\alpha$ = 0.10). Note changes in x-axis scaling between panels.

(Fig. 4h and l) and dormant biennial (increased K and Ca) (Fig. 4i and j) treatments. The effects of increased fire frequency within season were evident via trends toward decreased size of effect on N and increased size of effect on pH, for summer burns (Fig. 4g and l, respectively). In contrast, there were no trends across fire frequencies for dormant season burns for either of these variables. In addition to the results described above, a summary table of statistically significant treatment effects measured in 2015 (> 45 years post-fire) is available as supplementary data (Appendix A).

### 3.2. Soil responses and changes over time to prescribed fire

Non-metric multidimensional scaling for total forest floor soil properties resulted in a two dimensional solution with a final stress of 2.76. Axis 1 explained 50.6% of the variance in the effect size matrix for the years 1969 and 2015 and was positively correlated with P, K, Mg, pH, mass, and ash soil response variables (Fig. 5a). Dormant season burns were situated on the lower end of axis 1 with 1969 treatments in the upper left and 2015 remeasurements in the lower left of axis 1. In contrast, all summer season burns were located along the upper end of axis 1 with 1969 treatments occurring as a loose group in the upper right, whereas 2015 remeasurements occurred as a loose group in the lower right of axis 1. The summer annual burn was arrayed at the extremes of axis 1 and was consistent across years. Axis 2 accounted for 47.4% of variation in the same years and was negatively correlated with N, Ca, and OM (Fig. 5a). Treatments in 1969 were situated along the upper end of axis 2 and loosely grouped by season, although 2015 remeasurements were located along the lower end of axis 2 and loosely grouped by season.

NMDS ordination for the upper mineral soil converged on a two dimensional solution with a final stress of 5.61. Axis 1 explained 56.4% of the variance in the effect size matrix for the years 1969 and 2015 and was positively correlated with P (Fig. 5b). Summer season burns were located on the lower end of axis 1 as were all 2015 remeasurements with the exception of the 2015 dormant annual burn. In contrast, dormant season burns were located on the upper end of axis 1, with the exception of the 2015 dormant biennial burn, as were all 1969 treatments. NMDS axis 2 accounted for approximately 27.4% of the variability in the same years and was positively correlated with Ca, Mg, and pH (Fig. 5b). The 1969 burning treatments occurred as a loose aggregation in the center of the matrix, whereas no patterns in 2015 remeasurements were evident. Across years, the dormant annual burn was arrayed along the right end of axis 2.

NMDS ordination for lower mineral soil properties resulted in a one dimensional solution with a final stress of 6.44. Axis 1 explained 93.1% of the variability and was negatively correlated with K, Ca, and Mg (Fig. 5c). Across years, summer and dormant annual burns were positioned along the upper end of axis 1 and the summer annual burn displayed the greatest dissimilarity across time > 45 years following the last prescribed fire (Fig. 5c).

## 4. Discussion

### 4.1. Short–term effects of prescribed fire on soil properties

Our study leveraged a historical study site and dataset to investigate short-, intermediate-, and long-term effects of contrasting prescribed fire treatments in a naturally-regenerated red pine forest. Although Alban (1977) reported short-term findings from only a single year of measurements collected in 1969, we report trends in soil responses to prescribed fire treatments, using existing data collected over > 10 years (1959–1969) as well as a complete remeasurement in 2015. While we

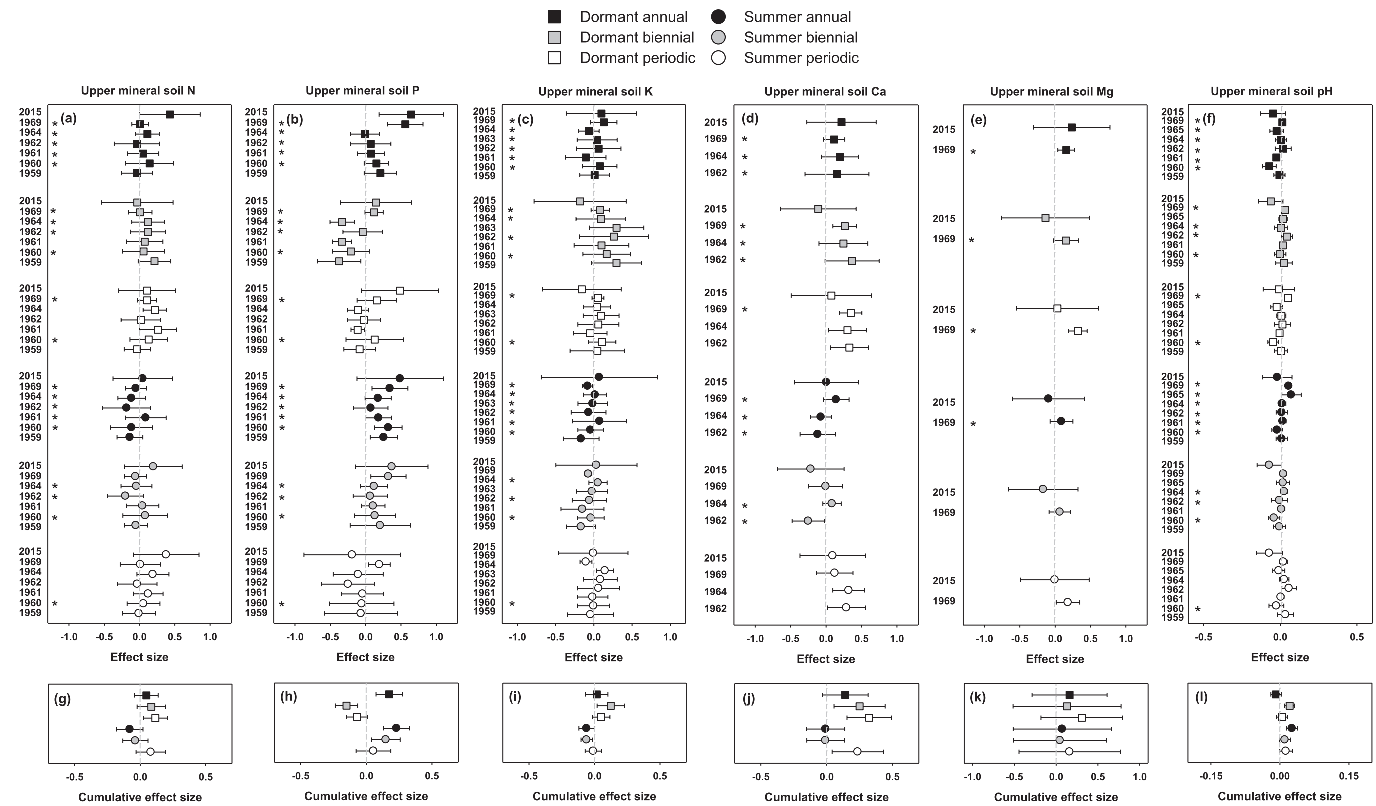


**Fig. 3.** Standardized effect sizes ( ± 90% confidence intervals) for upper (0–15 cm) mineral soil N, P, K, Ca, Mg, and pH. Within-year effect sizes are shown in upper panels, and cumulative effect sizes (across all years) are shown in lower panels. Symbol shape represents prescribed fire season, whereas shading represents frequency, for n = 4 replicates per treatment. Asterisks [*] in upper panels indicate the years in which prescribed fire treatments were conducted. Error bars that do not overlap the 0 effect size indicate a statistically significant treatment effect relative to the control, and non-overlapping error bars indicate statistically significant differences among treatments ($\alpha$ = 0.10). Note changes in x-axis scaling between panels.

present a more comprehensive understanding of short-term and intermediate effects of fire treatments, our findings often coincided with Alban (1977). Our results from the active burn period support general short-term findings of prescribed fire effects on soil properties, including decreased organic horizon depth, volatilization of N, increases in pH and base cations, and inconsistencies in P responses (Certini, 2005; Neary et al., 2005). Short- and intermediate-term soil responses to prescribed burns in our study differed by season of burning and the magnitude of effect size increased with increased fire frequency within season. Repeated burning, whether conducted in summer or in the dormant season, likely magnified the effects of fire by incrementally decreasing organic horizon mass and increasing combustion and subsequent loss of nutrients (Alban, 1977; Busse et al., 2014).

Alban (1977) reported short-term responses in the summer annual treatment resulted in the highest burn severity and greatest mass loss in forest floor horizons; these results corroborate our observations, and support similar findings following 20 years of prescribed fire treatments in loblolly pine (*Pinus taeda* L.) in South Carolina (Wells, 1971). Soil organic matter source material and quantity have direct effects on the amount and retention of nutrients by influencing CEC and pH (Neary et al., 2005). Fire causes changes in soil pH with volatilization of organic acids and an increase in base cations in post-fire ash (Johnson et al., 1991). Our results are comparable to values reported by several studies documenting only short-term increases in pH that are restricted to organic and upper mineral soil (Lunt, 1951; Metz et al., 1961; Smith, 1970; Wells, 1971; McKee, 1982). Nitrogen is a limiting plant nutrient in red pine ecosystems (Elliott and White, 1994) and is often volatilized in large quantities during fire, proportional to fire intensity and soil organic matter loss (Grier, 1975; Neary et al., 2005). This pattern is consistent with the trends we observed for decreased N for summer annual and biennial burns. The loss of N can have significant effects on post-fire plant recovery and long-term site productivity; however, burning may provide conditions that encourages N recovery via fixation of atmospheric nitrogen by leguminous symbiotic bacteria and recolonizing vegetation (Wells, 1971; McKee, 1982). This process may explain the absence of a cumulative treatment effect size we observed for N in the total forest floor horizon.

Soil elements including P, K, Ca, and Mg are resistant to volatilization and often occur as post-fire ash deposits (Neary et al., 1999; Bodí et al., 2014). Retention of these elements in soil is influenced by soil organic matter, CEC, pH, and clay content of post-fire soil (Alban, 1977). Soil elements are retained in the following order: $Ca2+ > Mg2+ > K+$, whereas P is a negatively charged ion often held as iron and aluminum precipitates and is more susceptible to nutrient losses (Lewis, 1974; Alban, 1977). The presence of base cations and P in post-fire ash is ephemeral, as they are often adsorbed to soil exchange sites, immobilized by soil microorganisms and colonizing vegetation, or translocated off-site via surface runoff or into the mineral soil (Neary et al., 1999; Wittenberg, 2012). The responses we observed in mineral soil properties agree with these patterns.

The trends in short- and intermediate-term responses to prescribed fire across years in mineral soil were similar to trends observed for total forest floor horizon soil responses. However, the magnitude of effect across years was less evident for upper mineral soil and further decreased in lower mineral soil, and supports other soil studies (Metz et al., 1961; Smith, 1970; Alban, 1977; McKee, 1982). Overall, our observations indicated that mineral soil property responses to prescribed fire were relatively minor and often ephemeral, and either remained at—or returned to—pre-burn levels shortly following fire; these results corroborate similar findings from other ecosystem types (Ahlgren, 1970; Smith, 1970; Wells, 1971; Binkley et al., 1992; Franklin et al., 2003). Nutrient retention and CEC of mineral soil is closely

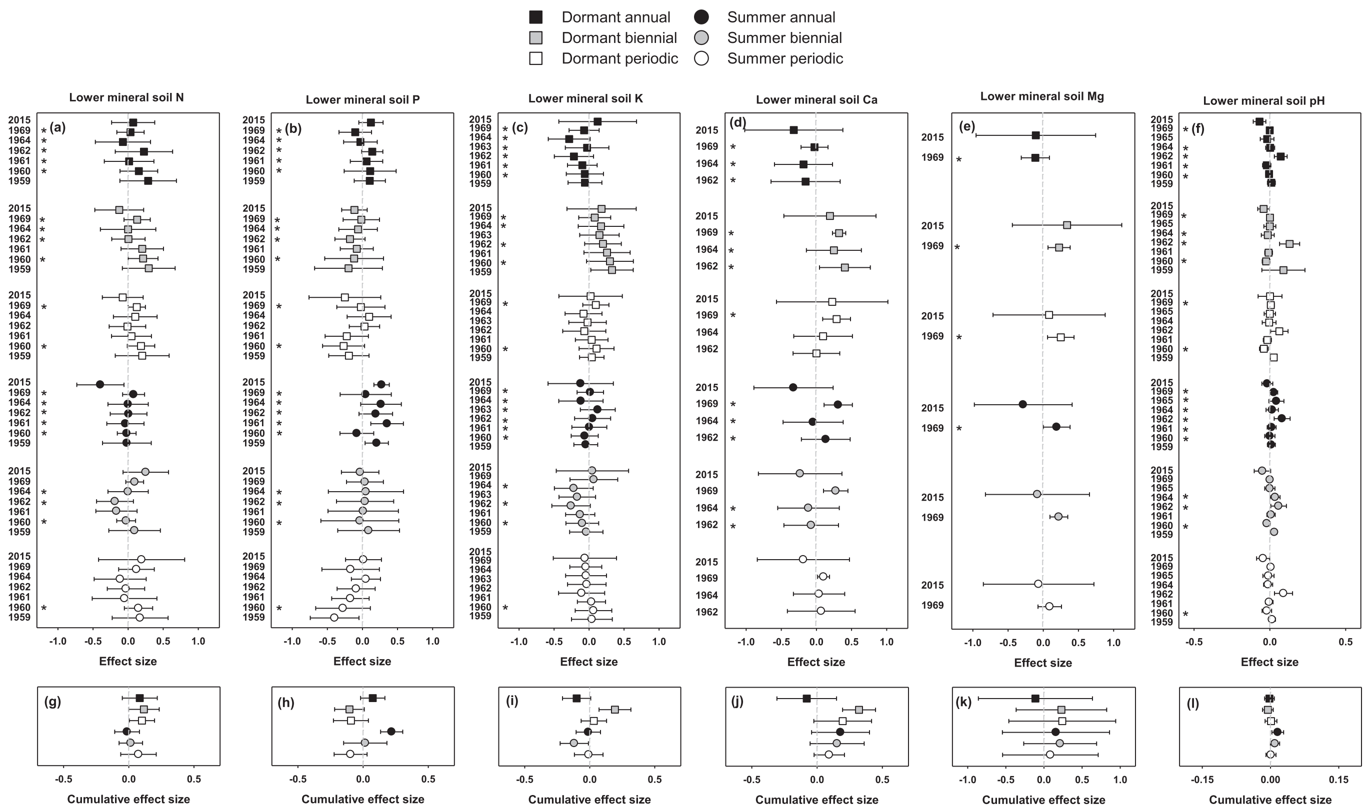

**Fig. 4.** Standardized effect sizes ( ± 90% confidence intervals) for lower (15–91 cm) mineral soil N, P, K, Ca, Mg, and pH. Within-year effect sizes are shown in upper panels, and cumulative effect sizes (across all years) are shown in lower panels. Symbol shape represents prescribed fire season, whereas shading represents frequency, for n = 4 replicates per treatment. Asterisks [*] in upper panels indicate the years in which prescribed fire treatments were conducted. Error bars that do not overlap the 0 effect size indicate a statistically significant treatment effect relative to the control, and non-overlapping error bars indicate statistically significant differences among treatments ($\alpha$ = 0.10). Note changes in x-axis scaling between panels.

related to soil texture and pH as well as soil organic matter (Helling et al., 1964). However, prescribed fire treatments had no influence on mineral soil bulk density or texture at any increment, consistent with studies in other regions (Lunt, 1951; Metz et al., 1961; Moehring et al., 1966), and trends in pH do not closely reflect nutrient stocks. Thus, short- and intermediate-term trends in upper and lower mineral soil N, K, Ca, and Mg may reflect the effects of increased CEC as post-fire organic matter and nutrients are translocated into the mineral soil (Metz 1961; Smith, 1970; Alban, 1977; McKee, 1982).

### 4.2. Long–term effects of prescribed fire on soil properties

Our study is the first to provide evidence that prescribed fire treatments had legacy effects on organic horizon and mineral soil properties in red pine ecosystems of the Lakes States region, and that effects persisted > 45 years since the last prescribed fire treatments. The overall trends we observed in persistent effects reflect similar short- and intermediate-term responses of our meta-analysis, and together suggest that soil responses to prescribed fire differed by season of burning and were further magnified by increased fire frequency within season. The annual fire frequency treatments, regardless of season, accounted for the majority of persistent effects among treatments in organic soil horizons and in upper and lower mineral soil increments.

The results of the NMDS for the total forest floor horizon support the findings that over time (1969–2015), season of burn was the primary contributor to observed trends in soil responses, and annual frequencies within season had a greater effect relative to other frequencies with time since fire. Comparatively, a study implementing a single summer prescribed fire conducted in a jack pine stand in Minnesota concluded that pH and nutrient content (N, P, K, Ca, Mg) increased relative to pre-burn conditions one year post-fire in organic soil, whereas following six years post-fire, only P content was decreased to below that of the pre-burn level (Ahlgren, 1970). Although we detected long-term effects for nutrients in the total forest floor horizon, Johnson et al. (2012) reported that soil variables (C, N, K, Ca, Mg) measured > 46 years among a post-wildland fire site and unburned forest site in California resulted in no persistent differences, with the exception of decreased P in the fire site.

Our results of the upper mineral soil NMDS over time also suggest that overall soil response differed primarily between seasons, whereas frequency of burns and time since fire were both relatively less important. Similar to our observations, a study in Michigan documented no significant differences in physical (bulk density) and chemical (total C, P, K, Ca, Mg, pH) soil properties in the 0–10 cm soil profile, with the exception of decreased total N, between 3 and 6 year post-wildland fire and undisturbed mature jack pine stands (LeDuc and Rothstein, 2007). However, the long-term increases in N and P in the upper mineral soil for the dormant annual treatment we documented are inconsistent with measurements in a pine plantation (*Pinus halepensis* Miller) recorded nine years following prescribed fire, which indicated decreases in N, P, pH, and C relative to pre-fire values in 0–5 cm mineral soil, although fire season was not reported (Alcaniz et al., 2016). In contrast to our observations, a study reporting the effects of a single spring prescribed burn in ponderosa pine stands in Oregon, documented no differences measured 12 years post-fire between burned and control plots in 0–5 cm mineral soil (Monleon et al., 1997). The persistent responses of soil properties in lower mineral soil we described (decreased N and pH; increased P) are similar to the study by Johnson et al. (2012) mentioned above, who reported long-term decreases in total N, P, and pH in fire sites measured in mineral soil increments at 30–45 cm, 30–90 cm, and 60–75 cm, respectively. Mineral soil is a poor conductor of heat and the effects of fire on mineral soil are often limited to the top few centimeters with the exception of high severity fires (Busse et al., 2014).

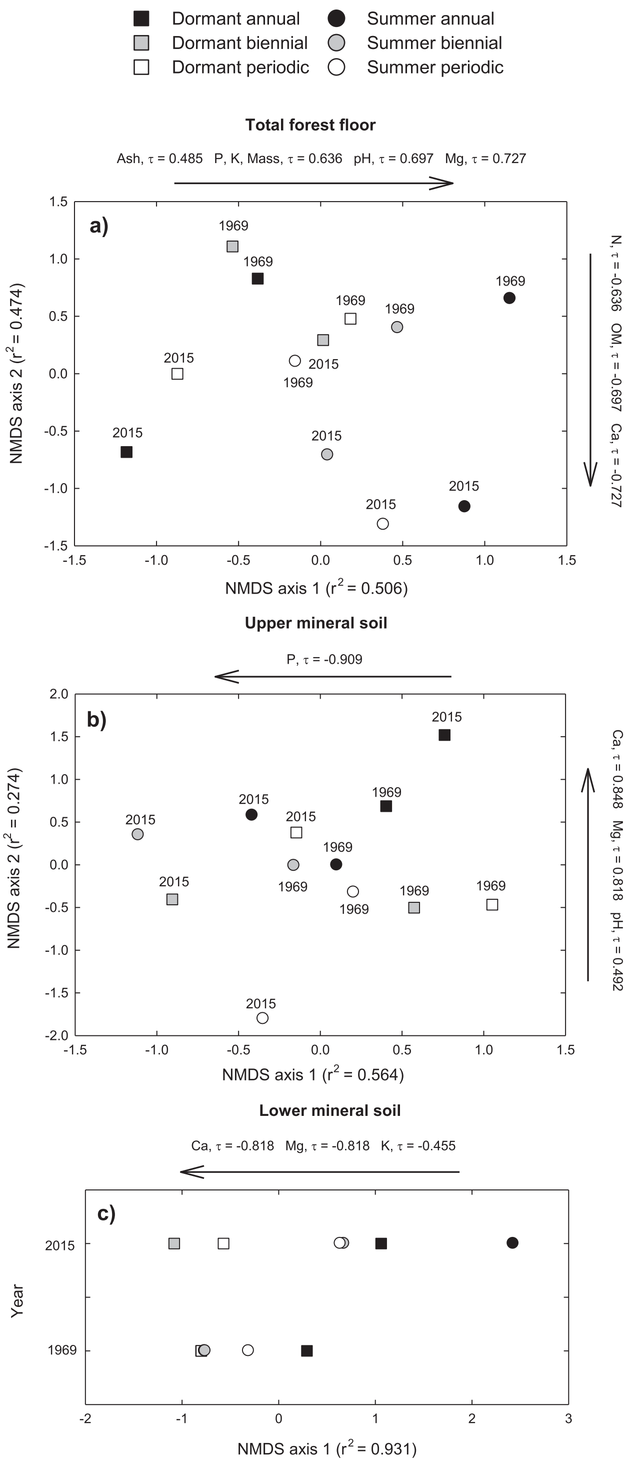


**Fig. 5.** Non-metric multidimensional (NMDS) ordination of standardized effect sizes (ES) of soil variable responses measured in 1969 and 2015 (> 45 years post-fire) in the total forest floor (litter, fermentation, humus) horizon and mineral soil upper (0–15 cm) and lower (15–91 cm) increments. Symbol shape represents prescribed fire season, whereas shading represents frequency, for n = 4 replicates per treatment. Correlation coefficients ($\tau$) between individual soil responses and NMDS axes at $\alpha = 0.10$ are shown.

The few persistent effects in upper and lower mineral soil properties we observed may be attributed to the highly permeable sandy soils and therefore relatively deep translocation of organic matter and soil nutrients at these depths.

### 4.3. Indirect effects of prescribed fire on soil properties

The resilience of fire-adapted communities and fire effects on soil properties are often a function of vegetation responses to fire disturbances (Keeley et al., 2011). Rapid recovery of re-sprouting understory shrubs, including hazel in red pine ecosystems, may mitigate nutrient losses through erosion and leaching and accelerate soil organic matter and nutrient recovery (Nyamai et al., 2014; Tappeiner and Alm, 1975). The original investigators at our study site reported that summer annual and biennial prescribed burns were most effective in reducing hazel densities, whereas dormant season burning resulted in prolific hazel sprouting (Buckman, 1964; Alban, 1977). The effects on hazel have persisted > 54 years since initiation of prescribed fire treatments (Scherer et al., 2016) and likely helps explain the trends in soil responses we observed. For example, previous studies in red pine forests have shown that high nutrient content in hazel foliage can increase soil organic matter as well as influence soil chemical composition and rates of nutrient cycling (Tappeiner and John, 1973; Tappeiner and Alm, 1975; Alban, 1977). Weyenberg and Pavlovic (2014) demonstrated that plant community composition in red and white pine stands is similar between pre- and post-burn sites treated with dormant season prescribed fires, whereas summer season burns resulted in statistically significant changes in vegetation including increases in species richness and diversity and a clear successional trajectory of pioneer species being replaced by shade tolerant species. A review of forest soils in Eastern North America concluded that long-term changes in soil were primarily driven by plant nutrient content and variations in soil organic matter quality and quantity, which differ significantly across vegetation types (Johnson et al., 1991). Therefore, quantifying local short- and long-term post-fire vegetation responses, including litterfall contributions and foliar nutrient content, will be critical in ongoing efforts to understand soil and ecosystem responses to fire.

## 5. Conclusions and management implications

Our study supports previous short-term findings of prescribed fire effects on soil properties reported in red pine and other ecosystem types and provides evidence that prescribed fire treatments had legacy effects on organic horizon and mineral soil properties > 45 years since the last prescribed fire. In general, the legacy effects of summer season burns decreased, whereas dormant season burns increased nutrient stocks in organic and mineral soil horizons, and the effects of fire intensified with increased fire frequency within season. Short- and long-term responses of soil properties to prescribed fire treatments are likely influenced not only by the direct effects of fire intensity, combustion of forest floor horizons, and redistribution of nutrients during fire. In addition, they are also influenced by the indirect effects of post-fire vegetation and litterfall via interactions between the aboveground and belowground components of a post-fire ecosystem, particularly given the permeable sandy soils at our study site. Our results suggest that summer burns may be a valuable approach to increase the variability in burn schedules representative of historical regional fire regimes and facilitate development of fire-dependent species, such as red pine, by reducing organic horizon depths and overall nutrient stocks. Implementing forest management activities that emulate natural disturbance regimes, such as the historical range of wildfire season and frequency, within a given ecological or geographic region, has been recommended for obtaining the best results in restoring and maintaining forest ecosystem structure, species composition, and soil nutrient dynamics (Knapp et al., 2009). To help achieve these ecosystem management objectives, managers could aim to include summer burns where possible, in contrast to the more common application of prescribed fires in the dormant season. Although high frequencies of prescribed fires may be useful for initiating ecosystem restoration (Agee and Skinner, 2005; Knapp et al., 2009), sustained annual and biennial frequencies of burn schedules are usually not logistically practical, regardless of season, because of weather, budgetary, and personnel constraints (Quinn-Davidson and Varner, 2012; Melvin, 2015). Annual and biennial fires are also more frequent than the historical fire regime in this region and ecosystem type (Bergeron and Brisson, 1990; Guyette et al., 2016). However, the absence of major persistent differences among treatments, and instances of similar direction of effects across treatments for the majority of soil properties we examined, suggest that summer season prescribed fires used to accomplish aboveground management objectives are not likely to result in strongly undesirable impacts to the mineral soil, such as increased nutrient stocks or changes in CEC, soil texture, and bulk density.

Although our results provide a unique comparison of contrasting fire seasons and frequencies, much more detailed information on weather conditions, fuel characteristics, phenology of vegetation, and firing techniques, as well as direct measures of fire intensity remain needed for these and other ecosystem types. These detailed data will be critical for improving our understanding of the relationships between fire behavior and fire effects over the short- and long-term after fire and for increasing the effectiveness of fire management activities to achieve specific management goals.

## Acknowledgments

We thank David Alban and Robert Buckman for establishing the design, implementing treatments, and devising protocols for this historical forest ecology research study as well as Brian Palik for supporting long-term record and site maintenance and Heather Jensen and Doug Kastendick for their assistance with data collection and logistical support. The authors are grateful for the support and assistance of Jon Dahl, Jaron Adkins, Dominic Uhelski, Eleanor Domer, and Kathleen Quigley. We also thank Melissa Thomas-Van Gundy, Benjamin Knapp, and two anonymous reviewers for comments that helped improve the manuscript. Financial support for this project was provided by the USDA Forest Service, State and Private Forestry, Forest Health Monitoring Program in St. Paul, MN. Partial salary support during this study was provided by an Academic Achievement Graduate Award from Michigan State University.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.01.021.

## References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Ahlgren, C.E., 1970. Some effects of prescribed burning on Jack Pine reproduction in northeastern Minnesota. University of Minnesota Agricultural Experiment Station Miscellaneous Report 94 Forestry Series 5, pp. 1–14.

Alban, D.H., 1972. The relationship of Red Pine site index to soil phosphorus extracted by several methods. Soil Sci. Soc. Am. Proc. 36, 664–666.

Alban, D.H., 1977. Influence on soil properties of prescribed burning under mature red pine. USDA Forest Service Research Paper No. NC-139, pp. 1–12.

Alcaniz, M., Outeiro, L., Francos, M., Farguell, J., Ubeda, X., 2016. Long-term dynamics of soil chemical properties after a prescribed fire in a Mediterranean forest (Montgri Massif, Catalonia, Spain). Sci. Total Environ. 572, 1329–1335.

Bergeron, Y., Brisson, J., 1990. Fire regime in red pine stands at the northern limit of the species' range. Ecology 71, 1352–1364.

Binkley, D., Richter, D., David, M.B., Caldwell, B., 1992. Soil chemistry in a loblolly/longleaf pine forest with interval burning. Ecol. Appl. 2, 157–164.

Bodí, M.B., Martin, D.a., Balfour, V.N., Santín, C., Doerr, S.H., Pereira, P., Cerdà, A., Mataix-Solera, J., 2014. Wildland fire ash: production, composition and eco-hydro-geomorphic effects. Earth Sci. Rev. 130, 103–127.

Bremner, J.M., 1965. Total Nitrogen. In: Black, C.A., (Ed.), Methods of Soil Analysis. Part 2: Chemical and Microbial Properties. American Society of Agronomy Inc., Madison, USA.

Brown, J.K., Smith, J.K., 2000. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 1–257.

Buckman, R.E., 1964. Effects of prescribed burning on hazel in Minnesota. Ecology 45, 626–629.

Busse, M.D., Hubbert, K.R., Moghaddas, E.E.Y., 2014. Fuel reduction practices and their effects on soil quality. Gen. Tech. Rep. PSW-GTR-241. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, p. 156.

Certini, G., 2005. Effects of fire on properties of forest soils: a review. Oecologia 143, 1–10.

Cleland, D.T., Crow, T.R., Saunders, S.C., Dickmann, D.I., MacLean, A.L., Jordan, J.K., Watson, R.L., Sloan, A.M., Brosofske, K.D., 2004. Characterizing historical and modern fire regimes in Michigan (USA): a landscape ecosystem approach. Landscape Ecol. 19, 311–325.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. J. Hydrol. 231–232, 195–206.

Dickmann, D.I., 1993. Management of red pine for multiple benefits using prescribed fire. North. J. Appl. For. 10, 53–62.

Drobyshev, I., Goebel, C.P., Hix, D.M., Corace III, G.R., Semko-Duncan, M.E., 2008. Pre- and post-European settlement fire history of red pine dominated forest ecosytems of Seney National Wildlife Refuge, Upper Michigan. Can. J. For. Res. 38, 2497–2514.

Elliott, K.J., White, A.S., 1994. Effects of light, nitrogen, and phosphorus on red pine seedling growth and nutrient use efficiency. For. Sci. 40, 47–58.

Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., Knapp, A., 2003. The Importance of land-use legacies to ecology and conservation. Bioscience 53, 77–88.

Franklin, S.B., Robertson, P.A., Fralish, J.S., 2003. Prescribed burning effects on upland Quercus forest structure and function. For. Ecol. Manage. 184, 315–335.

Frelich, L.E., 1995. Old forest in the Lake States today and before European settlement. Nat. Areas J. 157–167.

Govender, N., Trollope, W., Van Wilgen, B.W., 2006. The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. J. Appl. Ecol. 43, 748–758.

Grier, C.C., 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Can. J. For. Res. 5, 599–607.

Guyette, R.P., Stambaugh, M.C., Dey, D.C., Marschall, J.M., Saunders, J., Lampereur, J., 2016. 350 years of fire-climate-human interactions in a Great Lakes sandy outwash plain. Forests 7.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response rations in experimental ecology. Ecology 80, 1150–1156.

Heinselman, M.L., 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quat. Res. 3, 329–382.

Helling, C.S., Chesters, G., Corey, R.B., 1964. Contribution of organic matter and clay to soil cation-exchange capacity as affected by the pH of the saturating solution. Soil Sci. Soc. Am. Proc. 28, 517–520.

Henning, S.J., Dickmann, D.I., 1996. Vegetative responses to prescribed burning in a mature red pine stand. North. J. Appl. For. 13, 140–146.

Johnson, D.W., Cresser, M.S., Nilsson, S.I., Turner, J., Ulrich, B., Binkley, D., Cole, D.W., 1991. Soil changes in forest ecosystems: evidence for and probable causes. Proc. R. Soc. Edinb. 81, 81–116.

Johnson, D.W., Walker, R.F., McNulty, M., Rau, B.M., Miller, W.W., 2012. The long-term effects of wildfire and post-fire vegetation on Sierra Nevada forest soils. Forests 3, 398–416.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116–126.

Keeley, J.E., Pausas, J.G., Rundel, P.W., Bond, W.J., Bradstock, R.A., 2011. Fire as an evolutionary pressure shaping plant traits. Trends Plant Sci. 16, 406–411.

Knapp, E.E., Estes, B.L., Skinner, C.N., 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. Gen. Tech. Rep. PSW-GTR-224. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 1–80.

Krebs, P., Pezzatti, G.B., Mazzoleni, S., Talbot, L.M., Conedera, M., 2010. Fire regime: history and definition of a key concept in disturbance ecology. Theory Biosci. 129, 53–69.

LeDuc, S.D., Rothstein, D.E., 2007. Initial recovery of soil carbon and nitrogen pools and dynamics following disturbance in jack pine forests: a comparison of wildfire and clearcut harvesting. Soil Biol. Biochem. 39, 2865–2876.

Lewis, W.M., 1974. Effects of fire on nutrietn movement in a South Carolina pine forest. Ecology 55, 1120–1127.

Lunt, H.A., 1951. Liming and twenty years of litter raking and burning under red (and white) pine. Soil Sci. Soc. Am. Proc. 381–390.

McCune, B., Mefford, M.J., 2015. PC-ORD. Multivariate analysis of ecological data. Version 7.0. MjM Software, Gleneden Beach, OR.

McKee, W.H., 1982. Changes in soil fertility following prescribed burning on Coastal Plain pine sites. Res. Pap. SE-234. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, pp. 1–23.

Melvin, M.A., 2015. 2015 national prescribed fire use survey report. Technical Report 02-15, Coalition of Prescribed Fire Councils, Inc., pp. 1–17.

Metz, L.J., Lotti, T., Klawitter, R.A., 1961. Some effects of prescribed burning on Coastal Plain forest soil. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experimental Station, Station Paper No. 133, pp. 1–10.

Miesel, J.R., Goebel, P.C., Corace III, R.G., Hix, D.M., Kolka, R., Palik, B., Mladenoff, D., 2012. Fire effects on soils in Lake States forests: a compilation of published research to facilitate long-term investigations. Forests 3, 1034–1070.

Moehring, D.M., Grano, X., Bassett, J.R., 1966. Properties of forested loess soils after repeated prescribed burns. U.S. Department of Agriculture, Forest Service, Southern Forest Experimental Station, Research Note SO-40, pp. 1–4.

Monleon, V.J., Cromack Jr., K., Landsberg, J.D., 1997. Short- and long-term effects of

prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Can. J. For. Res. 27, 369–378.
Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffolliott, P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. For. Ecol. Manage. 122, 51–71.
Neary, D.G., Ryan, K.C., DeBano, L.F., 2005. Wildland fire in ecosystems: effects of fire on soils and water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 1–250.
Nowacki, G.J., Abrams, M.D., 2008. The demise of fire and "mesophication" of forests in the Eastern United States. Bioscience 58, 123–138.
NRCS, 2017. Web Soil Survey. USDA Natural Resources Conservation Service, Washington, DC. Available at websoilsurvey.nrcs.usda.gov/ (accessed 25 June 2017).
Nyamai, P.A., Goebel, P.C., Hix, D.M., Corace III, R.G., Drobyshev, I., 2014. Fire history, fuels, and overstory effects on the regeneration-layer dynamics of mixed-pine forest ecosystems of eastern Upper Michigan, USA. For. Ecol. Manage. 322, 37–47.
Quinn-Davidson, L.N., Varner, J.M., 2012. Impediments to prescribed fire across agency, landscape and manager: an example from northern California. Int. J. Wildland Fire 21, A-I.
Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin: statistical software for meta-analysis. Version 2.0., Sinauer, Sunderland, Massachusetts, USA.
Ryan, K.C., Knapp, E.E., Varner, J.M., 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front. Ecol. Environ. 11, 15–24.
Scherer, S.S., D'Amato, A.W., Kern, C.C., Palik, B.J., Russell, M.B., 2016. Long-term impacts of prescribed fire on stand structure, growth, mortality, and individual tree vigor in *Pinus resinosa* forests. For. Ecol. Manage. 368, 7–16.
Smith, D.W., 1970. Concentrations of soil nutrients before and after fire. Can. J. Soil Sci. 50, 17–29.
Staddon, W.J., Duchesne, L.C., Trevors, J.T., 1997. Microbial diversity and community structure of postdisturbance forest soils as determined by sole-carbon-source utilization patterns. Microb. Ecol. 34, 125–130.
Tappeiner, J.C., Alm, A.A., 1975. Undergrowth vegetation effects on the nutrient content of litterfall and soils in red pine and birch stands in northern Minnesota. Ecology 56, 1193–1200.
Tappeiner, J.C., John, H.H., 1973. Biomass and nutrient content of hazel undergrowth. Ecology 54, 1342–1348.
U.S. Forest Service, 2009. Experimental forests of the Northern Research Station. Nrs-Inf-07-09. U.S. Department of Agriculture, Forest Service, Northern Research Station, pp. 1–58.
Van Wagner, C.E., 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Canada Department of Forestry and Rural Developement, Forestry Branch, Publication No. 1229, pp. 1–30.
Van Wagner, C.E., 1970. Fire and red pine. In: Proceedings Annual Tall Timbers Fire Ecology Conference, pp. 211–219.
Wells, C.G., 1971. Effects of prescribed burning on soil chemical properties and nutrient availablity. Prescribed burning symposium proceedings. USDA Forest Service, Southeastern Forest Experiment Station, Ashville, NC, pp. 1–160.
Weyenberg, S.A., Pavlovic, N.B., 2014. Vegetation dynamics after spring and summer fires in red and white pine stands at Voyageurs National Park. Nat. Areas J. 34, 443–458.
Wittenberg, L., 2012. Post-fire soil ecology: properties and erosion dynamics. Israel J. Ecol. Evolut. 58, 151–164.
Zeleznik, J.D., Dickmann, D.I., 2004. Effects of high temperatures on fine roots of mature red pine (*Pinus resinosa*) trees. For. Ecol. Manage. 199, 395–409.