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Decades-old silvicultural treatments influence surface wildfire severity and post-fire nitrogen availability in a ponderosa pine forest

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Abstract

Wildfire severity and subsequent ecological effects may be influenced by prior land management, via modification of forest structure and lingering changes in fuels. In 2002, the Hayman wildfire burned as a low to moderate-severity surface fire through a 21-year pine regeneration experiment with two overstory harvest cuttings (shelterwood, seed-tree) and two site preparations (scarified, unscarified) that had been applied in a mature ponderosa pine forest in the montane zone of the Colorado Front Range in 1981. We used this event to examine how pre-fire fine fuels, surface-level burn severity and post-fire soil nitrogen-availability varied with pre-fire silvicultural treatments. Prior to the wildfire, litter cover was higher under both shelterwood and unscarified treatments than seed-tree and scarified treatments. Immediately after the fire in 2002, we assessed burn severity under 346 mature trees, around 502 planted saplings, and in 448 4 m^2 microplots nested within the original experimental treatments. In one-fourth of the microplots, we measured resin-bound soil nitrate and ammonium accumulated over the second and third post-fire growing season. Microplots burned less severely than bases of trees and saplings with only 6.8% of microplot area burned down to mineral soil as compared to >28% of tree and sapling bases. Sapling burn severity was highest in unscarified treatments but did not differ by overstory harvest. Microplot burn severity was higher under the densest overstory (shelterwood) and in unscarified treatments and was positively related to pre-fire litter/duff cover and negatively associated with pre-fire total plant cover, grass cover and distance to tree. In both years, resin-bound nitrate and ammonium (NH_4^+-N) increased weakly with burn severity and NH_4^+-N availability was higher in unscarified than scarified plots. The lasting effects of soil scarification and overstory harvest regime on modern patterns of surface burn severity after two decades underscores the importance of historic landuse and silviculture on fire behavior and ecological response. Unraveling causes of these patterns in burn severity may lead to more sustainable fire and forest management in ponderosa pine ecosystems.
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Keywords: Wildfire; Burn severity; Scarification; Forest floor disturbance; Overstory harvest cutting; Ponderosa pine; Soil N-availability

1. Introduction

Concern about catastrophic wildfire and modern changes to the structure and fire regimes of ponderosa pine (*Pinus ponderosa*) forests has stimulated interest in how land-management activities can alter fire severity and subsequent fire effects (Graham et al., 2004; Youngblood et al., 2005; Agee and Skinner, 2005). Recent severe wildfires have spurred efforts to unravel factors that influence fire behavior and fire effects in the ponderosa pine forests of the southwest (Fulé et al., 2001; Pollet and Omi, 2002; Finney et al., 2005), the northern Rockies (Scott, 1998; Pollet and Omi, 2002), the South Dakota Black Hills (Lentile et al., 2006), and the northwestern U.S. (Pollet and Omi, 2002; Lolley, 2005). These modeling efforts, experimental manipulations, and retrospective studies of wildfire have primarily addressed stand- and landscape-level influences on severe crown-fires. In comparison, factors that influence burn severity in ponderosa pine under less severe wildfire conditions and at smaller, within-stand spatial scales have rarely been investigated.

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Variation in fine-scale burn severity (i.e., <1–10 m) reflects the interaction of microclimate and microtopography (Franklin et al., 1997; Robichaud and Miller, 1999; Knapp and Keeley, 2006) as well as local fuel conditions (Brown et al., 2003). For surface fires, ground-level burn severity may vary with spatial patterns and abundance of low vegetation (Smith et al., 1993; McRae et al., 2005), fine and coarse woody debris (Lolley, 2005; Raymond and Peterson, 2005), and fine fuels such as needles, duff, and herbaceous litter (Sweeney and Biswell, 1961; Graham et al., 2004; Thaxton and Platt, 2006). Fuel moisture (Hartford and Frandsen, 1992; Valette et al., 1994), duff depth or loadings (Brown et al., 1985; Thaxton and Platt, 2006), and plant species (Smith et al., 1993) have been shown to influence burn severity (e.g., depth and duration of soil heating, fire spread rates, degree of fuel consumption).

Past land management influences burn severity at this fine scale, through its effects on species composition, stand structure, and configuration of surface, ladder, and crown fuels. For example, mechanical harvest decreases canopy density and modifies fuel loadings by removing or displacing woody fuels to the ground in patterns that vary with slash and yarding treatments (Agee and Skinner, 2005; Raymond and Peterson, 2005; Stephens and Moghaddas, 2005a). In ponderosa pine stands, herbaceous plants and associated litter that promote fire spread and fireline intensity, often increase in abundance under harvested patches or with increasing distance from trees (Klemmedson et al., 1990; Moore and Deiter, 1992; Wienk et al., 2004). In contrast, litterfall (needles, exfoliated bark) and duff accumulate more in close proximity to overstory crowns (Ryan and Frandsen, 1991) and may smolder and carry heat to soils and plant roots (Ryan and Frandsen, 1991; Miyanishi and Johnson, 2002; Stephens and Finney, 2002). Several factors can minimize local ground-level burn severity such as natural rockiness, scarification by animals, hand removal of fuels, or prior burning (Sweeney and Biswell, 1961; Knapp and Keeley, 2006; Thaxton and Platt, 2006). In managed forests, mechanical site-preparation can also alter the distribution of duff, litter, and herbaceous fuels that could contribute to heterogeneity in fire severity (Robichaud and Miller, 1999; Graham et al., 2004).

The influences of ground-level burn severity on patterns of N-availability are often overlooked despite nitrogen's role in shaping soil processes (Smithwick et al., 2005a), community structure and composition (Riegel et al., 1995; Metlen and Fiedler, 2006) and plant diversity (Gundale et al., 2006). On a landscape scale, soil N-availability often increases after fire for up to 2 years (Covington and Sackett, 1992; Monlean et al., 1997; DeLuca and Zouhar, 2000; Wan et al., 2001). While the magnitude of initial soil nitrogen increase is expected to vary with fire severity and degree of soil heating (Knoepp et al., 2005), studies relating soil nitrogen indices to ground-level burn severity are limited in scope and varied in responses (Antos et al., 2003; Gundale et al., 2005; Smithwick et al., 2005a). Lingering effects of past land use can also affect how soil nitrogen fluxes will respond to fire at this scale, because land use imposes lasting changes on the abundance, C:N quality, distribution, and microclimate of substrates that encounter fire (Compton and Boone, 2000; Murty et al., 2002; Duguy et al., 2007).

In 2002, the Hayman wildfire burned ~56,000 ha of Front Range forest in Colorado, including a 21-year ponderosa pine regeneration experiment where two overstory harvest cuttings (shelterwood, seed-tree) and two site preparations (soil scarified, soil unscarified) had altered forest conditions within the denser forest matrix (Shepperd et al., 2006). Prior to the wildfire, this open and even-aged stand of mature ponderosa pine supported few ladder fuels capable of contributing to crown fires and there were no differences among treatments in average crown base heights likely to influence fire severity (W.D. Shepperd, data on file, RMRS). However, pre-fire litter and duff cover was lower under seed-tree than shelterwood treatments and in scarified compared to unscarified plots (A.W. Schoettle, data on file, RMRS). Although the combination of extreme weather, parched and abundant fuels, and topographic setting led to crown fires over most of the Hayman burn (Finney et al., 2003), fire behavior was more diverse in our study site, torching few overstory trees and leaving a mosaic of burn conditions on the ground.

Understanding the mechanisms that drive variability in burn severity and subsequent fire effects within a forest will aid decisions related to fuel management and restoration of ponderosa pine ecosystems. In this study we evaluate how patterns of ground-level burn severity and subsequent nitrogen availability after wildfire varied with historic silvicultural treatments that were applied in 1981 in a Colorado Front Range ponderosa pine forest. We asked: (1) How did the distribution of burn severities vary among patches under trees, under saplings, and in small microplots? (2) Did burn severity or heterogeneity of burning vary with historic overstory harvest (shelterwood versus seed-tree) or site preparation (with or without soil scarification)? (3) Was burn severity correlated with pre-fire measurements of substrate cover, vegetation cover, or distance to tree? (4) Were differences in relative nitrogen availability (measured as resin-bound ammonium and nitrate) associated with burn severity or historic silvicultural treatments?

2. Methods

2.1. Site description

The study was conducted at Manitou Experimental Forest (MEF), a long-term research site of the U.S. Forest Service Rocky Mountain Research Station (RMRS). MEF is located in the Colorado Front Range of the southern Rocky Mountains, ~45 km northwest of Colorado Springs, CO, USA. The climate is temperate with mean daily air temperature ranging from 19 °C in July to −3 °C in January (Cheesman, CO weather station, data available at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?cochee). Typically, 75% of the 400 mm annual precipitation falls during the growing season between 1 April and 1 September (Johnson, 1945). During the 5 years prior to the Hayman wildfire, a severe drought drastically reduced summer rainfall (Bradshaw et al., 2003).

The research plots (39.14°N, 105.12°W) occupy gentle east-facing slopes or alluvial terraces at 2344–2390 m elevation. Surface soils are well-drained sandy loams and gravelly sandy loams of the Boyett-Frenchcreek complex (Mollic eutroboralfs and mixed Aridic Haploborolls) with 5–20% clay content (Moore, 1992). Soils are slightly erodible and have low organic matter averaging 1–4% in the top 35 cm (Moore, 1992). Vegetation is typical of the ponderosa pine-bunch grass type of the lower montane zone of south-central Colorado. An understory of sedges, bunch grasses dominated by Arizona fescue (*Festuca arizonica*), and a variety of forbs and low shrubs (*Arctostaphylos uva-ursi*, *Artemisia frigida*) grow beneath an open structured ponderosa pine stand (Shepperd et al., 2006). Dendrochronological evidence suggests that the stand originated ~170 years ago and has been subsequently harvested several times under management (Brown et al., 1999).

2.2. Historic treatments, study design, and pre-fire conditions

The original study was established on this site in 1981 to examine the effects of two overstory harvest cuttings (shelterwood with 50 trees ha^{-1}, seed-tree with 12 trees ha^{-1}) and site preparations (scarified, unscarified) on natural and planted ponderosa pine regeneration (Shepperd et al., 2006). Overstory and site preparation treatments were applied as whole plots (0.8 ha) and subplot (0.1 ha) effects, respectively, in a randomized split-plot design within seven replicated blocks (Fig. 1a). Site preparation treatments were replicated twice within each overstory treatment to compare responses of planted and natural pine regeneration. Within each 0.1 ha subplot, logging slash was removed, and either a 4 × 4 array of 4 m^2 microplots for natural regeneration or a 5 × 5 grid of planted seedlings was permanently marked and monitored (Fig. 1b). Scarified subplots for both planted and natural seedlings were rototilled down to ~15 cm with a small rubber-tired tractor, mixing ~2 cm of organic matter into the underlying mineral soil and completely removing herbaceous vegetation. Untilled buffers were left between natural seedling microplots and between rows of planted seedlings in scarified subplots. Scarification mimicked disking, a practice used operationally in the southwest and the Black Hills to promote the establishment of ponderosa pine (Boldt and Van Deusen, 1974; Schubert, 1974; Ronco and Ready, 1983; Shepperd et al., 2006).

Pre-fire fuel conditions and stocking levels at the study site (seed-tree: 2.3 m^2 ha^{-1}; shelterwood: 7.4 m^2 ha^{-1}) were typical of the open or savannah-like ponderosa pine sites sampled for fuels at MEF (≤9.2 m^2 ha^{-1}), where total woody fuel loadings averaged only 7.9 Mg ha^{-1} (M.A. Battaglia, data on file, RMRS). Study site basal areas were lower than the surrounding forest matrix that had been thinned from below to ~13.8 m^2 ha^{-1} the winter before the wildfire. Ladder fuels in all treatments were limited to sparsely distributed regeneration at mean densities ranging from 179 planted seedlings ha^{-1} to 296 naturally regenerated seedlings ha^{-1}. Heights of planted seedlings (mean treatment heights = 1.2–1.8 m) and natural regeneration (mean treatment heights = 0.41–0.71 m) were distinctly lower than average 1996 crown base heights of 6.6 m (shelterwood) and 7.0 m (seed-tree). Litter and duff thickness in comparable ponderosa pine stands at the MEF averaged 1.9 and 0.2 cm, respectively (M.A. Battaglia, data on file, RMRS). Although differences in soil disturbance associated with scarification were not apparent once vegetation recovered within a few years of rototilling, decreased litter/duff cover, increased gravel cover (A.W. Schoettle, data on file, RMRS) and increased mean surface soil temperature (Shepperd et al., 2006) were documented in scarified microplots after 15 and 18 years, respectively. Litter cover was also greater and total plant cover reduced under shelterwood than seed-tree treatments by 1996 (A.W. Schoettle, data on file, RMRS). As a result of early season drought in 2002, parched and prematurely dormant vegetation had formed a nearly continuous layer of fine fuels by early June (Finney et al., 2003).

2.3. Recent wildfire

In June 2002, the Hayman wildfire swept across ~56,000 ha of Front Range Colorado forests along the South Platte River corridor (Finney et al., 2003). The eastern flank of the fire burned across the 21-year-old Ponderosa Pine Study Site on 18 June. The Ponderosa Pine Study Site burned primarily as a low to moderate-severity fire, which resulted in only minor tree crowning and 14% tree mortality after 3 years. Mortality occurred primarily in two contiguous experimental blocks suggesting that fire behavior varied as fire moved across the larger experimental site (Fig. 1a). However, within each 0.8 ha experimental block, we assumed that fire behavior was influenced by comparable weather conditions. Thus, burn severity at the subplot-scale (0.1 ha) and microplot-scale (4 m^2) could be attributed to experimental treatments.

2.4. Sampling procedures

2.4.1. Burn severity

Within several weeks of the fire, we scored the dominant burn severity within a 1 m radius of 346 mapped trees (~5 m^2 sample area) and within a 15 cm radius of all of the planted saplings (~0.02 m^2 sample area) that were still alive prior to the fire (502 of the original 700). We also assessed fire severity in the 448 4 m^2 unplanted microplots. Burn severity was assessed on a scale of 1–4 as modified from ground char classes of Ryan and Noste (1985). We classified the dominant burn condition under trees or planted saplings, or estimated the proportion of microplot area that was categorized as (1) unburned, (2) burned aerial vegetation with intact duff and litter, (3) scorched litter with intact or partially charred duff, or (4) ash down to mineral soil. For microplots, we calculated a burn index by summing the products of each burn severity class (1–4) by its proportional cover (0.0–1.0) (Lentile, 2004).

2.4.2. Substrate and life-form cover prior to wildfire

To test associations of small-scale burn severity with pre-fire fine fuel loads, 1996 data for substrate cover, plant life-form

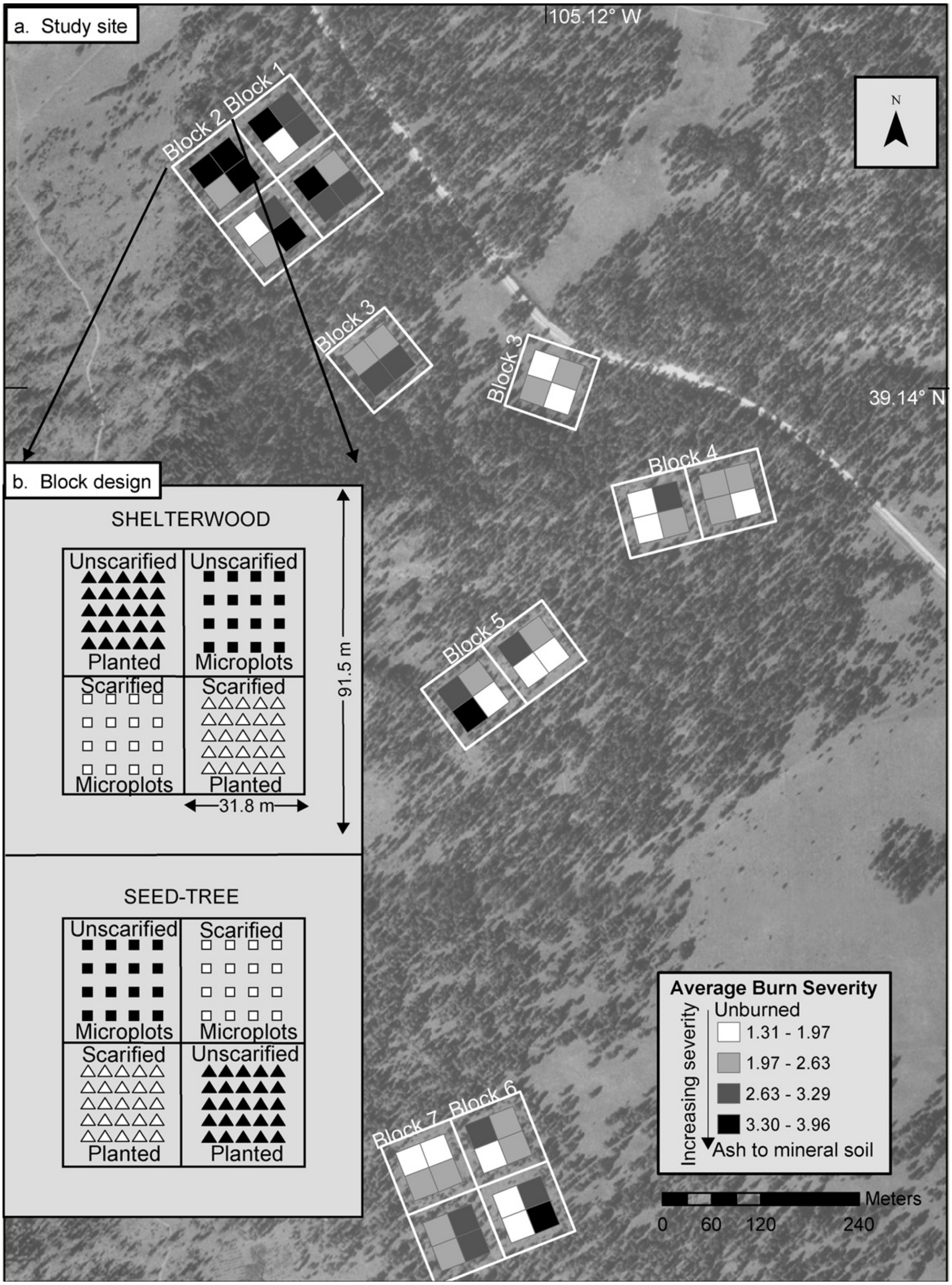

Fig. 1. Study design at Manitou Experimental Forest showing: (a) location of experimental blocks and average burn severity within each *overstory harvest* × *site preparation* subplot; (b) design of one block showing the layout of subplots with the 16 microplots and 25 planted saplings sampled for burn severity.

cover, and distance to nearest tree in the 448 microplots (A.W. Schoettle, data on file, RMRS) were used as a surrogate for pre-fire fuel loads. Litter, duff, and woody debris cover were combined to represent combustible fuels, while gravel, rock and bare soil cover were combined into a variable representing absence of fuels.

2.4.3. *Subsampling for nitrogen availability*

To examine how soil N-availability varied with small-scale burn severity and with historical silvicultural treatments, we monitored 112 of the 448 microplots during the second and third growing seasons after fire. Fire was not distributed uniformly within each of the 28 subplots or replicated in a balanced way among blocks, giving a highly skewed distribution of burn severities with some burn classes not available in particular blocks. Nonetheless, within each *overstory harvest* × *scarification* × *block* combination, we chose four microplots, randomly selected when possible (if more that one replicate of a burn severity class existed), to represent the available spectrum of burn severities.

We assessed relative N-availability by incubating ion exchange resin bags in these microplots during the second and third growing seasons after wildfire (Binkley and Matson, 1983). Each ~5 cm × 10 cm nylon resin bag was partitioned by waxed strip into two pouches containing 14.8 mL of either anion or cation exchange resins (Sybron Chemical Inc., Birmingham, NJ). Within each microplot, duplicate resin bags were clustered in a patch characteristic of the assigned burn severity, placing bags 5 cm below organic horizons with minimum disturbance to soils. Bags were incubated in place from May to October. Bag surfaces were cleaned of dirt and roots during retrieval, kept on ice in separate air-tight plastic bags during transit, and refrigerated until extractions. Resins were extracted with 100 mL of 2 M potassium chloride (KCl) and analyzed colorimetrically for NH_4^+-N and NO_2^- + NO_3^--N by Lachat injection flow autoanalyzer (Lachat Instruments Inc., Milwaukee, WI) according to Lachat Instruments *Quik Chem* Methods 107-06-2-A (2003) and 107-04-1-B (2003) in the USDA Forest Service RMRS Biogeochemical Lab. Nitrogen concentrations (μg/bag) were averaged among replicates prior to analyses. Bags that were flooded, buried by sediment, or chewed by animals were eliminated from analyses.

2.5. Analyses and sampling considerations

We visually compared relative frequency distributions of the four burn severity classes among microsites (i.e., under trees, under saplings, in unplanted microplots). For microplots, the proportion of cumulative area sampled rather than the frequency of each burn severity class was examined, since more than one class could be counted in each microplot.

Effect of overstory harvest on burn severity under trees was based on a paired *t*-test of average whole-plot burn severity. Analyses of treatment effects on burn severity under saplings and in microplots were conducted using SAS proc-mixed for a split-plot randomized complete block design (Littell et al., 2006; SAS 9.1, 2002–2003, SAS Institute Inc., Cary, NC, USA). The model tested fixed main effects (overstory harvest) and split-plot effects (site preparation) and their interactions on: (1) burn index for the 448 unplanted microplots; or (2) burn severity for the 502 planted saplings. Spatially dependent correlated error was accounted for by including microplot and sapling location in the covariance term of a spatial spherical model (Littell et al., 2006, pp. 437–478). Levene's test of homogeneity (Littell et al., 2006, pp. 343–411) assessed heterogeneity of variance among treatments, evaluating both model suitability and the homogenizing effects of treatments on burn severity.

We evaluated the effect of pre-fire conditions on burn severity at two scales. At the subplot scale (0.1 ha), we correlated average burn severity around planted sapling bases with density of live planted saplings just prior to fire using Spearman's rank correlation coefficient (ρ, $N = 28$). Sapling density of subplots was also included as a covariate in a split-plot mixed model of average sapling burn severity, with overstory harvest and site preparation as main and split-plot effects, respectively (Littell et al., 2006). The covariate was considered as an independent factor in the model since survival of planted saplings prior to the wildfire was not statistically dependent on site preparation in 2002 (Shepperd et al., 2006). To evaluate the relationship of burn severity index to pre-fire conditions at the microplot scale (4 m^2) we examined scatterplots of burn severity in the 448 microplots against pre-fire substrate cover, life-form cover, and distance to tree. Since pre-fire microplot conditions were also affected by treatments (A.W. Schoettle, data on file, RMRS), we could not include them as covariates in split-plot models, but instead examined relationships between pre-fire microplot conditions and residuals of burn severity from the microplot-scale, split-plot mixed model described above. Spearman's rank correlation coefficient (ρ) was used to quantify these non-normal data associations.

To test relationships of available nitrogen to burn severity and historic treatments, we regressed naturally log-transformed values for seasonally accumulated nitrate and ammonium (μg/bag) in 2003 and 2004 on burn severity, saved residuals, and tested residuals in a split-plot mixed model for effects of overstory harvest and site preparation on N-availability unaccounted for by burn severity.

Although we replicated sampling among and within pre-existing experimental blocks and attempted randomization of subsamples, nesting of samples within the single burn constituted pseudoreplication, limiting generalizations to other fires (van Mantgem et al., 2001). Nevertheless, the difficulty of simulating wildfire's extreme and variable impacts, such as the range of burn severities studied here, underscores the importance of post-wildfire research even in the absence of experimental controls (van Mantgem et al., 2001).

3. Results

3.1. Burn severity

3.1.1. Burn severity distribution by patch type

Wildfire burn severities differed in distribution among patch types (i.e., under trees, under planted saplings, in natural seedling microplots) (Fig. 2). The frequency distribution of burn severities was similar under trees and saplings (Fig. 2a and b); both experienced more intense burning than in microplots (Fig. 2c). Unburned conditions rarely occurred under trees or saplings but covered nearly 30% of the microplot area sampled (Fig. 2c) and occurred in >60% of all microplots (data not shown). Scorched vegetation underlain by litter and duff (burn severity 2) accounted for the greatest areal extent (45.5%) and frequency (80.6%) in microplots. Patches consumed by fire

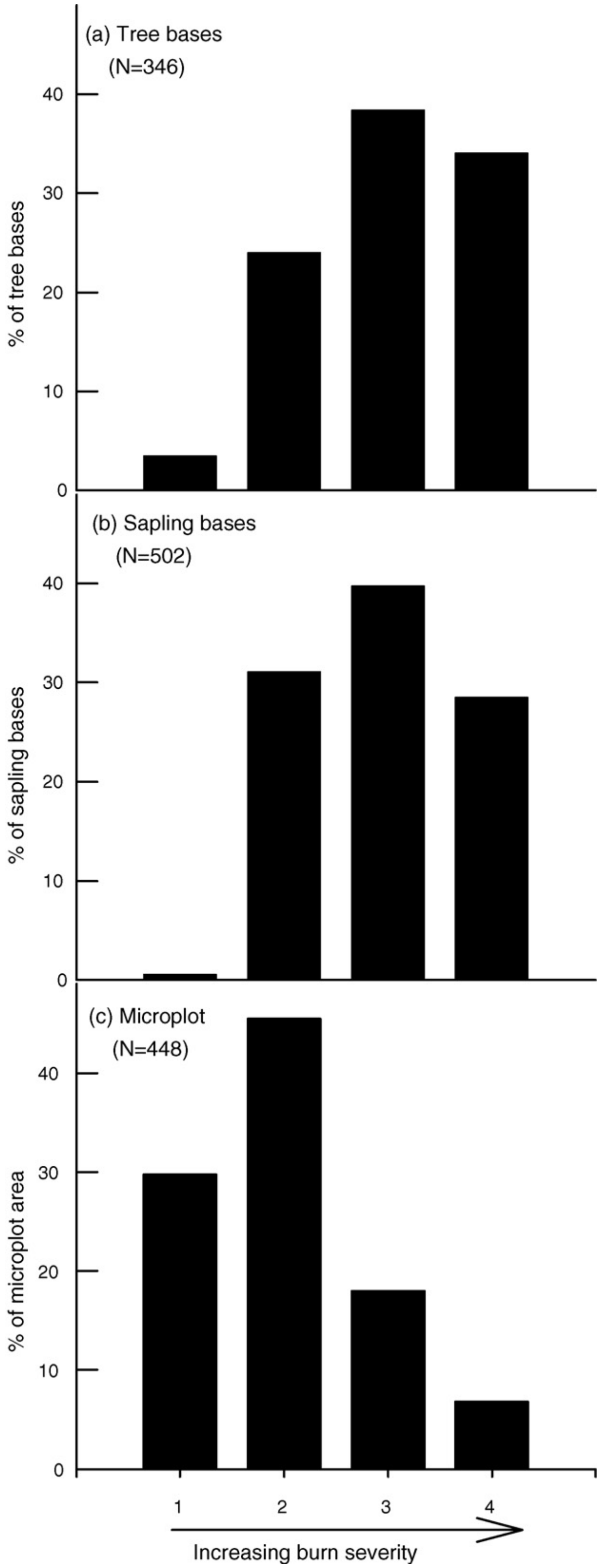

Fig. 2. Frequency distributions of four burn severity classes around bases of trees (a); planted saplings (b) are skewed towards higher burn severities as compared to the distribution of burn severities in microplots (c). Numbers in parenthesis (*N*) give sample size for each microsite. Microplot relative frequencies are the proportional area in each burn severity class.

down to mineral soil (burn severity 4) occurred rarely, in 6.8% of the area and 16% of all microplots.

3.1.2. Burn severity by treatment

Average burn severity around tree bases or planted sapling bases did not differ among shelterwood and seed-tree harvests (Fig. 3a and b). However, sapling bases burned more intensely in unscarified than scarified treatments (Fig. 3b). When averaged within the 28 *overstory harvest* × *site preparation* subplots, burn severity around sapling bases increased with pre-fire sapling density (Spearman rank correlation coefficient $\rho = 0.527$, $p = 0.004$, $N = 28$) but differed by site preparation even when sapling density was included as a covariate in the split-plot mixed model (Fig. 4). Microplot burn severity was greater in unscarified than in scarified treatments (Fig. 3c) and more severe beneath shelterwood than under seed-tree overstories (Fig. 3c). The distribution of the most severely burned class (ash to mineral soil) differed by site preparation both under saplings and in microplots, occurring more than two times as frequently in unscarified than in scarified treatments. On average, microplots burned most severely in unscarified, shelterwood treatments. Interactions between overstory harvest and site-preparation treatments were not significant.

3.1.3. Burn heterogeneity by treatment

Among sapling bases, and to a lesser degree among microplots, heterogeneity in burn severity was lower in scarified compared to unscarified treatments (Levene's test on residuals of burn severity: sapling bases, $F_{1,12.7} = 11.86$, $p = 0.0045$; microplots, $F_{1,12} = 4.05$, $p = 0.067$). Adjustments to the split-plot model reflecting heterogeneous variance were made, accordingly. Overstory treatments had no effect on heterogeneity of burn severity for either microplots or sapling bases.

3.1.4. Correlation of burn severity with pre-fire microplot conditions

A weak positive correlation was evident between 1996 litter/duff cover and microplot burn severity (Fig. 5a). In contrast, burn severity decreased with increasing 1996 bare ground cover (Fig. 5b), distance to large tree (Fig. 5c), 1996 grass cover ($\rho = -0.271$, $p < 0.0001$, not shown) or total 1996 vegetation cover ($\rho = -0.178$, $p < 0.0001$, not shown), but variability was great. Pre-fire 1996 sedge cover showed no relationship with burn severity ($\rho = 0.007$, $p = 0.876$, not shown). Confounding effects of treatments and pre-fire substrate conditions on burn severity are evident in scatterplots, where unscarified and shelterwood microplots sampled a more limited range of substrate conditions (Fig. 5). When pre-fire microplot conditions were correlated with residuals of the split-plot model of burn severity to remove treatment effects, these relationships were weakened (litter/duff: $\rho = 0.285$, $p < 0.0001$; bare substrate: $\rho = 0.301$, $p < 0.0001$; distance: $\rho = -0.231, p < 0.0001$; grass cover: $\rho = -0.161, p < 0.0006$; total cover: $\rho = -0.009$, $p = 0.855$; sedge cover: $\rho = -0.009$, $p = 0.842$).

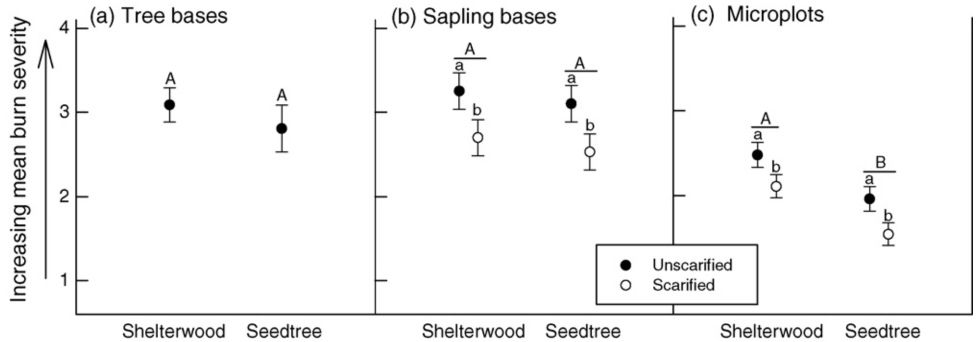

Fig. 3. Mean burn severity under trees (a) and saplings (b), and mean burn index in microplots (c) for overstory harvest and site preparation treatments averaged over seven experimental blocks. Error bars ±1 S.E. Significant differences in burn severity among overstory harvest treatments or site preparation within harvest treatments at $\alpha \leq 0.05$ are indicated with different upper case and lower case letters, respectively. Statistical results in: (a) are based on two-tailed paired *t*-test ($t_6 = 1.48$, $p = 0.19$) and in (b) and (c) are based on Proc Mixed Split-Plot Analyses for (b) saplings (overstory harvest $F_{1,6} = 0.53$, $p = 0.4944$; site preparation $F_{1,11.8} = 33.94$, $p < 0.0001$); (c) microplots (overstory $F_{1,6} = 25.06$, $p = 0.0024$; site preparation $F_{1,12} = 13.21$, $p = 0.0034$).

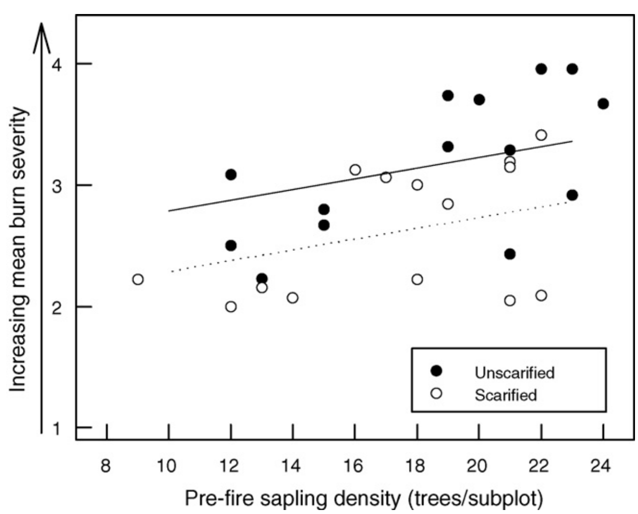

Fig. 4. Average subplot burn severity under planted saplings increases with pre-fire sapling density and decreases with scarification. Parallel lines indicate fitted slopes from covariate analysis for unscarified (solid) and scarified (dashed) treatments. Covariance analyses with Proc Mixed: overstory harvest: $F_{1,6} = 0.02$, $p = 0.902$; site preparation $F_{1,11} = 27.57$, $p = 0.0003$; sapling density $F_{1,11} = 5.77$, $p = 0.028$.

3.2. Effects on N-availability

3.2.1. N-availability with burn severity

If pre-fire treatments were ignored, resin-bound NO_3^--N and NH_4^+-N showed very weak but significant increases with fire severity in 2003 and 2004 (2003 NH_4^+-N: Fig. 6a, $N = 102$; 2004 NH_4^+-N: Fig. 6b, $N = 103$; 2003 NO_3^--N: Fig. 6c, $N = 102$; 2004 NO_3^--N: Fig. 6d, $N = 101$). Average daily accumulation of resin-bound NO_3^- per bag nearly doubled between the second and third growing season since fire (mean ± 95% CI: 3.33 ± 0.94 μg/(bag day) in 2003, 6.41 ± 1.85 μg/(bag day) in 2004). During this period, average daily accumulation of resin-bound NH_4^+-N was nearly steady (mean ± 95% CI: 3.38 ± 1.16 μg/(bag day) in 2003, 3.96 ± 1.61 μg/(bag day) in 2004).

3.2.2. N-availability with treatment

N-availability was unaffected by overstory harvest after removing effects of burn severity (Table 1, SAS Mixed model split-plot results for residuals). In contrast, site-preparation accounted for significant variability in NH_4^+ availability in both 2003 and 2004 after effects of burn severity were removed, with lower available NH_4^+-N in scarified than unscarified microplots (Table 1, Fig. 6a and b). Nitrate residuals differed with scarification only in 2003, when available NO_3^- was lower in scarified than unscarified treatments (Table 1, Fig. 6d). When separate linear regressions were examined for scarified and unscarified microplots, significant relationships ($p < 0.05$) between N-availability and burn severity were found for 2003 NH_4^+-N only; additional trends were observed ($p < 0.1$) but only for unscarified microplots. Comparing N-availability among scarified and unscarified microplots that were

Table 1
SAS mixed-model treatment effects on residuals from regressions of seasonally accumulated resin-N against microplot burn severity (year 2003 and 2004 are the second and third growing season after wildfire, respectively)

Fixed effect			Overstory			Site preparation		
Year	Variable[a,b]	N	DDF[c]	F	p	DDF[c]	F	p
2003	NH_4^+-N	102	6.0	2.04	0.203	11.8	11.3	0.006
2003	NO_3^--N	102	6.3	0.32	0.588	10.8	5.17	0.044
2004	NH_4^+-N	103	5.9	1.18	0.320	11.7	4.87	0.048
2004	NO_3^--N	101	6.4	2.69	0.149	10.5	0.80	0.391

[a] Ammonium and nitrate were natural logarithm transformed prior to regression analyses.
[b] Residuals from the listed variable were used as the dependent variable in the model statement.
[c] Denominator degrees-of-freedom calculations are based on the Kenward–Roger approximation method (Littell et al., 2006).

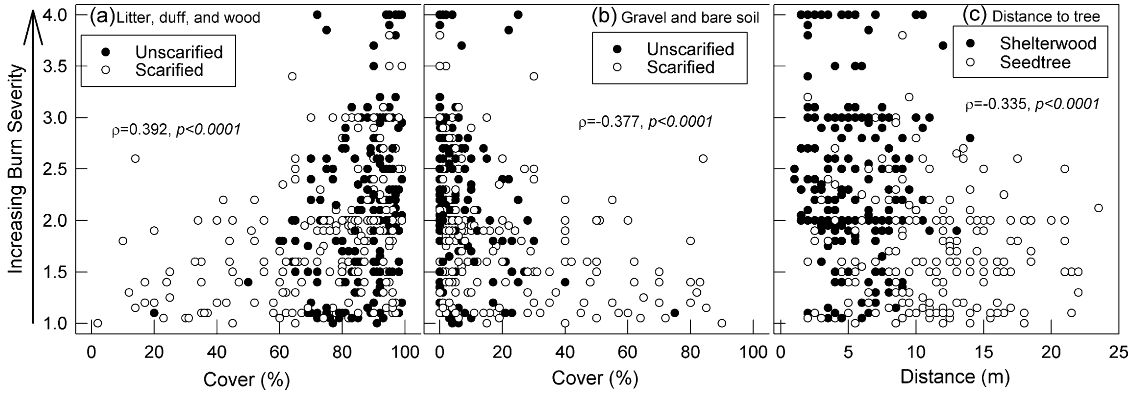

Fig. 5. Burn severity index in 4 m^2 microplots increases with pre-fire 1996 measurements of (a) litter, duff and woody debris cover; decreases with (b) gravel and bare soil cover; (c) distance to overstory tree. Segregation of microplots by pre-fire treatments (indicated in legend) suggest confounding effects of silvicultural treatment and pre-fire microplot conditions on burn severity. Spearman correlation coefficients (ρ) and p values are given.

''minimally burned'' (≤5% burning of litter, duff, or soil) minimized confounding effects of burn severity on differences in N-availability with scarification. In these minimally burned microplots, distributed among all seven experimental blocks, scarification was associated with lower resin-extractable NO_3^- and NH_4^+ in 2003 (ANOVA: NO_3^--N $F = 7.37$, $N = 63$, $p = 0.0086$; NH_4^+-N $F = 14.97$, $N = 63$, $p = 0.0003$) but no difference in N-availability in 2004 (ANOVA: NO_3^--N $F = 0.67$, $N = 61$, $p = 0.4164$; NH_4^+-N $F = 2.14$, $N = 62$, $p = 0.149$).

4. Discussion

4.1. Patchiness of fuels and ground-level burn severity

Across much of the Hayman wildfire landscape, extreme environmental conditions (e.g., wind, fuel moisture) overwhelmed the mitigating effects of fuel modifications on burn severity (Martinson et al., 2003). However, near the edges of the wildfire, in our less severely burned experimental site, fine-scale burn severity patterns on the ground reflected variation in

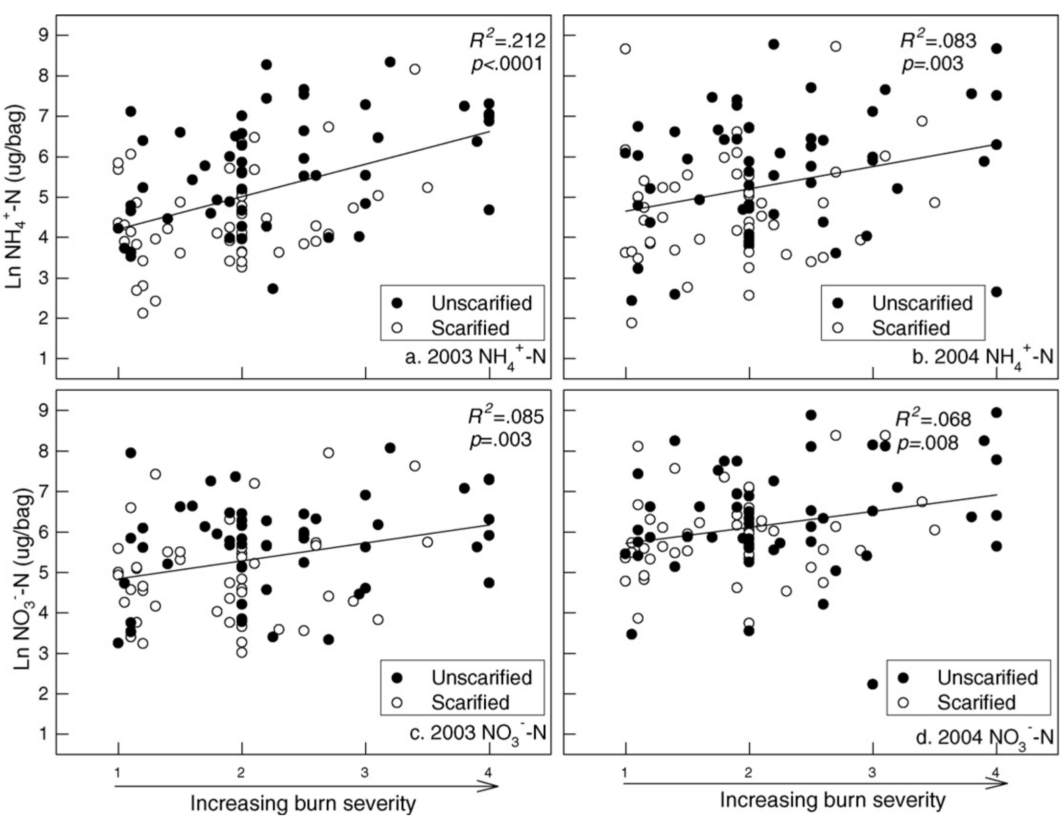

Fig. 6. N-availability increases weakly with burn severity for (a) resin-accumulated NH_4^+-N in 2003 and (b) 2004; for (c) resin-accumulated NO_3^--N in 2003, and (d) 2004. Scarified microplots (open circles) tend to have lower N-availability than unscarified microplots (closed circles) at a given burn severity. Analyses of residuals (Table 1) test these differences by removing effects of burn severity.

fuels among microsites (tree bases, sapling bases, microplots) and among historic silvicultural treatments (overstory harvest, scarification).

4.1.1. Fine fuels and ground-level burn severity

Accumulations of litter and duff associated with tree abundance or proximity of sample sites to trees may explain the local hotspots of burn severity. Frequency of high severity burned patches (down to mineral soil) and average burn severity were greater at the bases of trees or planted saplings than in small systematically located microplots that rarely contained tree bases and averaged 8 m from a tree (A.W. Schoettle, data on file, RMRS). Furthermore, average burn severity was higher in subplots supporting greater live sapling density prior to wildfire, and in microplots under the denser shelterwood than the seed-tree treatments. Higher burn intensity or fuel consumption near to trees has been linked to greater duff and litter depth under tree crowns (Miyanishi and Johnson, 2002; Hille and Stephens, 2005; Varner et al., 2005), and lower fuel moisture due to canopy interception of precipitation (Miyanishi and Johnson, 2002; Hille and Stephens, 2005). Data collected by Schoettle on this study site in 1996 revealed lower pre-fire litter/duff cover under seed-tree versus shelterwood treatments and a decrease in litter/duff cover with distance from overstory trees. This pattern is consistent with findings of lower litter mass in more open ponderosa pine forests (Klemmedson et al., 1990) and lower duff/litter abundance in mechanically thinned mixed-conifer stands (McIver et al., 2003; Stephens and Moghaddas, 2005b). Under these more open canopies, lower needle inputs (Klemmedson et al., 1990), higher temperature (Kaye and Hart, 1998; Wetzel and Burgess, 2001; Boyle et al., 2005), and increased decomposition (Klemmedson et al., 1985) can contribute to lower litter/duff abundance. In contrast, under denser tree cover or near tree bases, duff accumulation may facilitate prolonged smoldering and downward heat penetration to mineral soils (Covington and Sackett, 1984; Hartford and Frandsen, 1992; Miyanishi, 2001). Variability in fine herbaceous fuels may also account for differences in burn severity among patch types and harvest treatments, because these fuels tend to carry flame quickly (Finney et al., 2003), consequently transferring less heat downward to forest floor and soils (Hartford and Frandsen, 1992; Neary et al., 1999). Greater pre-fire cover of total vegetation and grass potentially minimized fire severity on the ground by facilitating faster fire spread in seed-tree compared to unscarified shelterwood treatments. Negative relationships between grass or total vegetation cover and burn severity support this relationship.

4.1.2. Overstory structure and ground-level burn severity

Forest structure may influence ground-level burn severity through effects on microclimate and patchiness of woody fuels. Higher within-stand wind speeds and dryer microclimates expected under the more open seed-tree treatments (Scott, 1998; Agee and Skinner, 2005; Lolley, 2005) could facilitate increase flame length, faster fire spread, and decreased burn duration at local microsites. Differences in woody fuel loads that have been shown to control surface fire intensity in conifer forests (McIver et al., 2003; Raymond and Peterson, 2005) were unlikely to contribute to burn severity differences at our site because loadings remained uniformly low following removal of logging debris in 1981. Treatment differences in density of small diameter trees or crown-base heights were not found prior to the wildfire (W.D. Shepperd, data on file, RMRS) and therefore were unlikely to explain the range of burn severities. Burn severity around planted saplings did not differ between shelterwood and seed-tree harvests, suggesting that fuels associated with individual saplings (dead and live branches, needle litter) may have masked differences in litter/duff cover associated with density of overstory trees.

4.2. Scarification and ground-level burn severity

Historic scarification by rototilling was associated with decreased burn severity, both around planted saplings and in microplots, despite a two decade span for forest floor recovery prior to the Hayman wildfire. The importance of fine fuels to fine-scale burn severity is underscored by the positive relationship between pre-fire litter/duff cover and burn severity measured at the 4 m^2 scale and the decreases in pre-fire litter/duff cover in scarified compared to unscarified microplots. These results suggest a link between decreased fire severity and persistent loss in ground fuels capable of sustaining combustion and spread. Elsewhere, unburned or less intensely burned patches in burned matrices have been attributed to rocky microsites (Price et al., 2003), rock and bare ground cover (Knapp and Keeley, 2006) and experimental removal of fine fuels (Thaxton and Platt, 2006). Experimental removal of duff in ponderosa pine stands has also been demonstrated to decrease fire intensity and soil heating (Covington et al., 1997). However, removal of litter alone by raking ponderosa pine bases did not lead to anticipated declines in burn severity and duff consumption by prescribed fire, presumably because remaining duff thickness and exposure favored drying and burning (Swezy and Agee, 1991).

The persistent litter/duff reductions in scarified sites after 21 years are surprising given the continuous needle inputs under the forested canopies, the relatively slow decay rates of ponderosa pine litter (Covington and Sackett, 1992; Monleon and Cromack, 1996) and the speedier recovery of organic layers in other ponderosa pines stands after duff removal by burning (Busse et al., 2000). Scarification at our site may lead to longer-lasting changes in surface horizons than other disturbances (e.g., Compton and Boone, 2000; Duguy et al., 2007) because of enhanced erosion potential (Johnson, 1945; Gary, 1986), sustained declines in plant inputs, enhanced temperatures of exposed mineral soils (Shepperd et al., 2006), and potentially increased decomposition rates (Salonius, 1983). Decreased soil carbon and microbial biovolumes in scarified treatments at our site (Esquilín, 2006) suggest that initial mixing of forest floor and mineral soils also led to losses of below-ground organic materials which had not recovered by the time of wildfire.

4.3. Nitrogen availability and ground-level burn severity

Our findings of increasing resin-bound-N with burn severity are not unexpected, given evidence of increased N-availability soon after fire in conifer forests (Ryan and Covington, 1986; Monlean et al., 1997; Wan et al., 2001; Certini, 2005). Following wildfire in the South Dakota Black Hills, Lentile (2004) observed increasing levels of soil N-availability with increasing stand burn-severity. Stand-level studies relating post-fire N-dynamics to crown burn severity can miss the underlying small-scale heterogeneity in burn conditions on the ground, consequently overlooking potential relationships between ground burn severity and inorganic soil nitrogen, which often varies at scales of meters or less (Antos et al., 2003; Smithwick et al., 2005a). Our trend of increasing N-availability with burn severity at a 4 m^2 scale may reflect the potential for litter and duff cover to influence the degree of substrate consumption by fire and subsequent N-availability. Alternatively, this trend may reflect a relationship between NH_4^+-N availability and forest floor abundance in its unburned state (e.g., MacKenzie et al., 2004). Positive correlations between degree of fuel consumption and N-availability (i.e., net N-mineralization, N-leaching, initial N-availability) have been demonstrated at small scales at other sites (Covington and Sackett, 1992; Gundale et al., 2005, 2006), but are not consistently observed after burning of forest floor fuels, even at a scale of 1 m^2 (Antos et al., 2003).

Small-scale burn severity explained only a small proportion of the variation in N-availability. This unexplained variability may partially reflect the transient nature of post-burn inorganic N-availability (Wan et al., 2001; Antos et al., 2003; Smithwick et al., 2005b), which may have already declined by the second and third growing season after wildfire. Degree of surface burning may not always be mirrored by below-ground processes because unburned patches may overlay senescing roots from severely burned plants a distance away. Inherent soil variability, the redistribution of ash, charcoal, and sediments by pocket gophers or wind, and the restructuring of vegetative and microbial communities after fire may also contribute to patchiness in N-dynamics (Huntly and Inouye, 1988; Newland and DeLuca, 2000; DeLuca et al., 2006; Esquilín, 2006).

4.4. Nitrogen availability with historical treatments

Scarification was associated with lower N-availability in 2003 and lower NH_4^+-N availability in 2004, even though the scarification treatment had been applied more than two decades earlier. These differences were evident even when effects of burn severity were removed. The subset of scarified microplots with $\leq$5% burning of litter, duff, or soil also showed lower N-availability than unscarified treatments during the second growing season, a difference that may have been ameliorated by ash redistribution and root inputs from dying plants by the third growing season after fire. Impacts of scarification on N-availability previously have been shown to differ across habitats, with patterns obscured by differences in climate, forest floor conditions, and degree and depth of soil mixing or organic soil removal (MacKenzie et al., 2005; Powers et al., 2005). Our results 21 years after scarification were generally similar but longer-lasting than those reported from a broad range of conifer plantations where complete removal of forest floor organic matter led to reduced N-availability, mineralizable N, or total soil N after 4–10 years (Ohtonen et al., 1992; Munson and Timmer, 1995; Bulmer et al., 1998; Merino et al., 2004; Powers et al., 2005). However, no decrease in N-availability after 10 years (MacKenzie et al., 2005), or evidence for transient increases after 1 year (Smethurst and Nambiar, 1990) were found after mechanical site preparations mixed forest floor and mineral soil in other forest types.

Several mechanisms may account for the differences we observed in N-availability 21 years after scarification. Initial structural changes associated with rototilling such as reduced forest floor thickness, redistribution of organic matter, disruption of aggregate structure (Bulmer et al., 1998), removal of plants as N-competitors, and changes in physical properties such as increased temperatures and soil aeration (Ohtonen et al., 1992; Wetzel and Burgess, 2001; MacKenzie et al., 2005) may have lead to short-term increases in net N mineralization and nitrification as observed in other disturbed forest soils (Smethurst and Nambiar, 1990), with subsequent nitrate loss through leaching (Blumfield et al., 2005). The long-term decreases in litter/duff cover reported here and decreases in soil carbon with scarification (Esquilín, 2006) suggest that carbon substrates for microbial decomposition have never caught up to levels found in unscarified plots despite litter accumulations over the last two decades. Limited organic substrates for N-mineralization and lower ion-exchange capacity associated with loss of soil carbon plus the hypothesized initial N loss may explain the long-term reductions in N-availability in scarified plots. However, changes in microbial communities and additions of inorganic N with recent wildfire may restore levels of N-availability in scarified plots (Esquilín, 2006). Regardless of the mechanisms involved, scarification of these soils clearly had profound and prolonged effects on components of this ecosystem.

5. Conclusion

Across the western U.S., long-term efforts to restore ponderosa pine forests to pre-European-American structure and function are utilizing experimental combinations of harvest and prescribed burning (Kaye and Hart, 1998; Youngblood et al., 2005; Gundale et al., 2005). The overlay of a 2002 wildfire on a past harvest and site-preparation experiment in this Colorado Front Range forest provided an opportunity to examine effects of pre-existing silvicultural treatments on small-scale fire severity and fire effects. Results suggest that even decades-old changes in stand structure and substrate, although not effective in stopping fire spread, modified small-scale burn severity within a low to moderate-severity wildfire. Elevated burn severities in forest floor patches containing relatively greater litter/duff cover (e.g., tree and sapling bases, shelterwood substrates, and unscarified patches) support the hypothesis that treatments influenced burn severity through the effects of litter/duff quantity on fire behavior. Increased sapling density in planted subplots was also associated with increased burn severity on the ground. Litter- and duff-rich patches close to trees or in locations without a history of scarification may have burned for longer periods, leading to more prolonged heating of mineral soil, as well as subsequent increases in N-availability. Lower N-availability in scarified plots may be a consequence of less severe burning, as well as a legacy of initial declines in N-availability associated with changes to forest floor and microclimates. Over time, declines in N-availability in scarified plots may be obscured by N inputs from burning. The combination of harvest and site preparation treatments contributed to a patchwork of burn severities across this natural experiment, with subsequent fine-scale effects on N-availability. Understanding the spatial variability in burn conditions will require assessments that reflect the different microsites and fuel conditions present. This understanding will be important in planning fuel mitigations and restoration treatments that minimize wildfire hazard and severe ecosystem consequences, even at small scales.

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