Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 250 (2007) 156–166
Forest Ecology and Management
www.elsevier.com/locate/foreco

Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest

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Received 3 December 2006; received in revised form 1 May 2007; accepted 7 May 2007

Abstract

More than a century of fire exclusion and past timber management practices in many Sierra Nevada mixed-conifer forests have led to increased stand densities and fuel accumulation, with a corresponding risk of large, high severity wildfires. To reduce hazardous fuel accumulations and restore the health and natural processes of forest ecosystems, fuel management programs often employ thinning and prescribed fire treatments, both alone and in combination. We evaluated forest floor and mineral soil chemical and physical characteristics following these treatments in a managed Sierra Nevada mixed-conifer forest using a fully replicated study design with four separate treatments: THIN, BURN, THIN + BURN, and an untreated CONTROL. Compared to the CONTROL, the BURN and THIN + BURN treatments consumed a large amount of the forest floor, reducing the mass and depth by more than 80%. These treatments reduced the forest floor C and N pools by more than 85%, resulting in reductions of 25 Mg C ha^{-1} and more than 700 kg N ha^{-1} from the forest floor. Despite these large losses from the organic horizons, no significant differences in mineral soil total C and N pools were detected among treatments. Compared with the CONTROL and THIN treatments, the BURN and THIN + BURN significantly increased the mineral soil NO_3-N concentration, pool of inorganic N, pH, and exposed bare soil. The THIN + BURN treatment significantly increased the concentrations of NH_4-N and exchangeable Ca relative to the CONTROL. No significant differences in the net rates of nitrification, N mineralization, or bulk density were detected among the four treatments. The BURN treatment reduced mineral soil C concentration and CEC, while the THIN + BURN treatment had the greatest increase in inorganic N. Fire effects on soil pH and inorganic N were moderated in skid trails due to reduced fuel continuity and consumption. In light of the current management emphasis on hazardous fuels reduction, we recommend that researchers investigating fire effects in harvested stands include skid trail influences in their study design.

Keywords: Fuel treatment; Soil; Sierra Nevada; Skid trail; Forest restoration

1. Introduction

Currently, more than 72 million ha of Federal land in the United States (US) are estimated to be at risk from unusually severe fires (USDA-USDI, 2006). This is due in part to more than a century of fire exclusion and past timber management practices that have led to increased stand densities and fuel accumulation (Parsons and DeBendeetti, 1979; Skinner and Chang, 1996; Stephens, 2000; Taylor, 2000; Hessburg et al., 2005).

Many Sierra Nevada mixed-conifer forests historically experienced frequent, low-to moderate-severity fire regimes (Stephens and Collins, 2004; Moody et al., 2006). Reintroduction of fire into forest ecosystems is often recommended to restore its ecological function as a disturbance agent, as well as a means to reduce hazardous fuel loads (Arno, 1996). Prescribed fire programs, however, are often constrained by hazardous fuel conditions, unfavorable weather, air quality regulations on smoke (Neary et al., 1999), and budgetary procedures (Stephens and Ruth, 2005). In lieu of fire, fuels may be removed and manipulated mechanically by harvesting, thinning, pruning, and chipping (Mutch and Cook, 1996; Keyes and O'Hara, 2002; Agee and Skinner, 2005; Peterson et al., 2005; Stephens and Moghaddas, 2005b). Such fire surrogate treatments are often designed to reduce fuels and create forest structures that resemble historic stand conditions. Current US policies for Federal lands emphasize the use of prescribed fire, either alone or in combination with mechanical, chemical, biological, or manual techniques to meet fuel reduction objectives (USDA-USDI, 2000; HFRA, 2003).

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doi:10.1016/j.foreco.2007.05.011

Forest floor depth and mass influence fire behavior, regulate physical soil protection, and affect nutrient pool size. Forest floor nitrogen (N) and carbon (C) content can influence decomposition rates, affecting nutrient availability and plant productivity (Swift et al., 1979; Aber and Melillo, 1980; Fisher and Binkley, 2000; Hyvönen et al., 2000). While the organic material on the forest floor serves as a nutrient reservoir that can slowly be incorporated into the mineral soil by decomposition (Swift et al., 1979), fire can short-circuit the biological decomposition pathway and rapidly cycle nutrients from organic to inorganic forms (Neary et al., 1999; Busse and DeBano, 2005). Biological processes such as N mineralization can also be enhanced following fire (Covington and Sackett, 1992). As a result of biological and non-biological means, increases in inorganic N availability are frequently reported following fire. Many forest ecosystems are considered to be N limited (Vitousek and Howarth, 1991), and short-term increases in productivity are often observed following fire.

Due to the emphasis on large-scale fuel treatments in managed forests, there is a need to understand the potential ecological impact of these treatments on the soil resource. In commercial timberlands, soils are often managed to maintain site productivity. For example, nearly all soil N is contained in organic matter (Busse and DeBano, 2005), and N losses from forest floor consumption and volatilization during fires are not readily replaced (Harvey et al., 1989). Following prescribed fire in the eastern Sierra Nevada, Murphy et al. (2006) determined that N losses from the forest floor represented less than 10% of the total N pool of the site. However, they caution that repeated burning could substantially impact N pools.

Many studies on the effects of fuels management utilize a retrospective approach, comparing burned or harvested sites to untreated controls. In many cases, no pre-treatment data are available to confirm that the controls were similar to the treated areas before the disturbance, the disturbance is poorly documented, or treatments were widely separated in both space and time (Powers, 1989). Physical, chemical, and biological properties of soil can vary widely in both space and time, which can confound apparent treatment effects to soils in retrospective disturbance studies. In this study, we limited these confounding factors by sampling all units before and after implementing fuel treatments, minimizing the temporal and spatial separation of the treatments, and also conducting all measurements in untreated controls.

The objectives of this study were to evaluate forest floor and mineral soil chemical and physical characteristics following fire and fire surrogate treatments in a managed Sierra Nevada mixed-conifer forest using a fully replicated study design with four separate treatments. The treatments included: (1) prescribed fire to reduce potential wildfire severity and reintroduce fire as an ecosystem process (BURN), (2) mechanical thinning and mastication to modify forest structure as a surrogate for fire (THIN), (3) mechanical thinning and mastication followed by prescribed fire to mechanically manipulate stand structure, reduce surface fuels, and reintroduce fire as a disturbance agent (THIN + BURN), and (4), an untreated control to represent managed timber stands with continued fire exclusion (CONTROL). Treatment effects on forest floor mass, depth, C, and N content were evaluated, as well as effects on mineral soil nutrient status including C and N (total and inorganic), net rates of N mineralization and nitrification, pH, exchange properties, and base cations. Effects to soil physical properties were also measured, including bulk density, soil strength, and the extent of exposed bare soil.

2. Materials and methods

2.1. Study site

Treatment units were located on the western slopes of the central Sierra Nevada at the University of California Blodgett Forest Research Station (38°54′N, 120°39′W) near Georgetown, California. Elevation ranges from 1100 to 1410 m. Total annual precipitation averages about 160 cm, falling mostly as rain from October to early May. Mean monthly air temperature ranges from 4 °C in December and January to 21 °C in July and August (Blodgett Forest Research Station, 2006). Vegetation consists of mixed-conifer forest comprised of sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws), white fir (*Abies concolor* (Gord. & Glend.) Lindl.), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), California black oak (*Quercus kelloggii* Newb.), tan oak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder), bush chinkapin (*Chrysolepis sempervirens* (Kell.) Hjelmg.), and Pacific madrone (*Arbutus menziesii* Pursh) (Stephens and Collins, 2004). The mineral soils are underlain by Mesozoic granitic material and are predominantly classified as the Holland and Musick series (fine-loamy, mixed, semiactive, mesic Ultic Haploxeralfs) (Olson and Helms, 1996).

The study site is actively managed commercial timberland that has supported several harvest entries. Legacy effects from these activities are reflected in the stand structure, species composition, and transportation network used to access the stands. Skid trail systems can affect physical properties of both the forest floor and mineral soil, and we surmised that skid trails would influence the overall treatment effects. To determine if skid trails were an important component of the soil and forest floor response to treatments, we stratified all samples into two categories, those collected within skid trails, and those outside of skid trails. As a result, treatment effects can be presented based on the overall stand, skid trail areas, or non-skid trail areas.

2.2. Experimental treatments

This research was conducted at one of 13 study sites implementing the national Fire and Fire Surrogates Study (FFS). Treatments at all sites were designed to modify stand structure such that, following treatment, 80% of the dominant and co-dominant trees would survive a wildfire modeled under 80th percentile weather conditions (Weatherspoon and Skinner, 2002). A second objective was to create a stand structure that maintained or restored forest characteristics and processes such as snag and coarse woody debris recruitment, diversity of floral and faunal species, and seedling establishment. The forest floor and soils component was designed to determine the consequences of the fuel treatments on key aspects of forest floor and soil structure, function, biogeochemistry, and biodiversity (Weatherspoon and McIver, 2000). At the Blodgett study site, three replicates each of four treatments, including no treatment (CONTROL), prescribed fire (BURN), mechanical treatment (THIN), and mechanical treatment followed by prescribed fire (THIN + BURN) were randomly assigned to 12 treatment units. The treatment units ranged from 14 to 29 ha, and data collection was restricted to a 10-ha core area in the center of each unit.

CONTROL units received no treatment during the study period (2000–2005). With no pre-treatment of fuels, BURN units were burned in 2002 using strip head-fires (Martin and Dell, 1978), one of the most common ignition patterns used to burn forests in the Western US. THIN units were treated in two stages—commercial harvest followed by mastication. In 2001, stands were heavily thinned from below (Graham et al., 1999) to maximize crown spacing, retain 28–34 $m^2\ ha^{-1}$ of basal area, and produce an even mix of residual conifer species. Trees were felled, bucked, and limbed using a chainsaw, and boles were removed with a rubber tired or track laying skidder. Following the harvest, approximately 90% of understory trees between 2 and 25 cm diameter at breast height were masticated in place using an excavator-mounted rotary masticator. The THIN + BURN treatments first underwent the same treatment as the THIN units. In addition, they were prescribed burned using a backing fire in the fall of 2002. The four treatments were fully described by Stephens and Moghaddas (2005a). Table 1 displays mean stand characteristics and fuel loadings in each treatment category before and after treatment implementation. Treatment effects on stand structure, fuel loads, and potential fire behavior and severity were reported by Stephens and Moghaddas (2005b).

All BURN and THIN + BURN units were treated with prescribed fire during a 15-day period, between 23 October and 6 November 2002, with most active ignitions occurring at night between 16:00 and 09:00. This was preferred because relative humidity, air temperature, wind speed, and fuel moistures were within ranges to be ignited safely while producing the desired fire effects. During the burn operations period, recorded on-site daily high and low temperatures ranged from 14 to 18 °C and 2 to 8 °C, respectively. Recorded high and low relative humidity ranged from 37 to 96% and 12 to 47%, respectively. Wind speeds, including gusts, were less than 8 $km\ h^{-1}$ during the entire burn period. To reduce the chance of accidental escape, fires were ‘‘held’’ during the day with minimum active ignitions. The last rainfall had occurred in June 2002, and the prescribed burns were conducted in what was considered ‘‘fire season.’’

In BURN units, the dominant fire behavior consisted of surface fires with observed flame lengths less than 1 m and occasional torching of trees less than 25 cm diameter followed by approximately 32–36 h of burnout of duff, stumps, and larger diameter woody debris. Rates of spread were typically less than 1.5 $m\ min^{-1}$ for both backing and strip head fires (Kobziar et al., 2006). Observed fire behavior was similar in THIN + BURN units, however residence time of flaming combustion was longer due to a continuous fuel bed of masticated material. In BURN units, flaming combustion typically lasted up to 10 min, while flaming combustion in THIN + BURN units lasted up to 20 min.

2.3. Forest floor and soil sampling

Pre-treatment sampling of forest floor and mineral soil materials occurred from late May to August 2001. Post-treatment sampling occurred from June to August 2003. During each sampling period, litter, duff, and mineral soil were collected from twenty 0.04-ha plots within each of the 12 treatment units (240 plots total). Six subplots were established at each plot for a total of 1440 subplots across the 12 treatment units. Each subplot was categorized as occurring in a skid trail

Table 1
Stand and fuel loading characteristics before and after implementation of fuel treatments (ave ± S.E.)

	CONTROL	THIN	BURN	THIN + BURN
Trees (number ha^{-1})				
Pre-treatment	1100.9 (67.3)	972.0 (226.2)	850.1 (16.8)	823.3 (187.3)
Post treatment	1109.5 (84.2)	428.7 (139.7)	441.5 (32.1)	238.9 (20.9)
Basal area ($m^2\ ha^{-1}$)				
Pre-treatment	55.1 (3.1)	51.9 (2.0)	49.4 (2.2)	55.1 (1.5)
Post treatment	56.4 (3.0)	40.9 (0.8)	(47.8) (2.5)	39.3 (2.5)
Canopy cover (%)				
Pre-treatment	69 (6)	66 (4)	68 (1)	63 (5)
Post treatment	75 (5)	58 (1)	65 (3)	51 (4)
1-, 10-, 100-h fuels (Mg ha^{-1})†				
Pre-treatment	11.6 (1.6)	9.9 (1.0)	12.0 (2.2)	12.2 (1.4)
Post treatment	14.2 (1.1)	17.1 (0.8)	4.4 (1.0)	4.8 (0.2)
1000-h fuels (Mg ha^{-1})†				
Pre-treatment	24.5 (4.7)	30.4 (8.0)	29.2 (4.4)	30.9 (3.3)
Post treatment	29.5 (3.2)	29.2 (7.9)	5.9 (1.0)	8.2 (2.5)

† Surface fuel diameter classes: 1-h (<0.64 cm), 10-h (0.64–2.54 cm), 100-h (2.54–7.62 cm), 1000-h (>7.62 cm).

or outside of a skid trail. Skid trails were identified based on visual indications of past equipment use, such as a waterbarred equipment trail, a skid trail bed with cut and fill slope, a trail wide enough for a skidder that is clear of vegetation, except brush or young trees, with skinned or cat-faced trees along the edges of and facing the trail, and rutting in long, linear depressions resembling equipment tracks. The percent area of skid trails was determined as the percent of subplots identified in skid trails. At each subplot, litter and duff depths were measured and samples were collected from 15 cm × 15 cm frames. Mineral soil core samples were collected at each subplot from the 0–15 cm depth. For litter, duff, and soil, the six subsamples were pooled into two categories: skid trail samples or non-skid trail samples. Forest floor material was oven-dried at 65 °C, and soil samples were air-dried. During post-treatment field sampling, each subplot was examined for evidence of burning, including scorched or ashed litter or duff, and scorched woody materials.

Soil physical properties were also measured at each of the six subplots. Soil strength was measured adjacent to each soil core using a recording cone penetrometer (Rimik CP20, Agridry Rimik Pty Ltd.). The six penetrometer readings were similarly grouped into skid trail and non-skid trail measurements. The percent cover of bare mineral soil was visually estimated at each of the 240 0.04-ha plots.

2.4. Sample processing and analysis

Litter and duff were ground through an intermediate Wiley mill (Thomas Scientific). A subsample was ground in a ball mill to pass a 60-mesh screen for total C and total N determinations by combustion (Nitrogen/Carbon Analyzer 112-200-11, Carlo-Erba). Bulk density of litter and duff samples were calculated using equations developed for California coniferous forests (van Wagtendonk et al., 1996, 1998). Coefficients required to calculate litter and duff bulk densities were arithmetically weighted by the basal area fraction (Stephens, 2001).

Soil bulk density was determined based on the total mass and volume of each sample. Air dry soils were sieved to <2 mm, and a subsample was dried to constant weight at 105 °C to correct for moisture. A subsample from each soil was ground in a ball mill to pass a 60-mesh screen for total C and total N determinations by combustion. Soil pH was determined in a 1:2 soil-to-solution mixture of 0.01 M $CaCl_2$ (Kalra and Maynard, 1991) using a glass electrode pH meter (Accumet 15, Fisher Scientific). Cation exchange capacity (CEC) was determined by the ammonium acetate (pH 7) method (Sumner and Miller, 1996) and exchangeable bases in the NH_4OAc leachate were measured by atomic absorption spectrometry.

2.5. N status and transformations

At each of the 240 plots, net N mineralization and nitrification rates were assessed with aerobic, *in situ* incubations using the buried bag method (Hart et al., 1994). Intact soil cores from the 0–15 cm layer were placed in 25 μm polyethylene bags and incubated in the field for 30 days, beginning from mid May to mid June. An additional core was collected at each plot for analysis of initial NO_3 and NH_4 status. Within 12 h of collection, incubated samples were extracted with 2 M KCl and the filtrate was frozen for transport and analysis. In the laboratory, NH_4 and NO_3 were determined from the thawed samples using a flow-injection analyzer (QuikChem 8000, Lachat Instruments).

2.6. Statistical analysis

Treatment effects on soil properties were evaluated using analysis of covariance (ANCOVA). To remove the influence of pre-treatment differences among treatment groups, the pre-treatment data was modeled as a covariable (Selvin, 1995). Interaction effects were tested by adding a crossed (treatment × pre-treatment) term. Differences were considered significant at the $p < 0.05$ level. If differences among treatments were significant, the Tukey-Kramer HSD test was used to make multiple comparisons among treatment groups (Sall et al., 2001). Normality of treatment group means and homogeneity of variance among means were assessed using the Shapiro-Wilk test and O'Brien's test, respectively. All analyses were conducted using JMPIN statistical software (SAS Institute, Inc., 2001).

3. Results

3.1. Organic horizons

The BURN and THIN + BURN treatments significantly reduced the depth and mass of litter and duff materials relative to both the CONTROL and THIN treatments (Table 2). As a result, the pools of total C and total N in the organic horizons were significantly reduced in the burned units relative to CONTROL. The concentration of total C in litter was significantly decreased in the BURN and THIN + BURN treatments relative to CONTROL (Table 2). In the BURN treatment, the concentration of total C in both litter and duff significantly decreased relative to CONTROL. Total N concentrations in the litter and duff did not differ significantly among treatments (Table 2). Due to consumption of litter and duff, the area of exposed mineral soil significantly increased in the BURN and THIN + BURN treatments relative to the CONTROL and THIN treatments (Table 4).

3.2. Mineral soil

The concentration of soil total C in the BURN treatment was significantly reduced below the CONTROL, but there were no significant differences in the total C pool among treatments (Table 3). There were no significant differences in total N among treatments. However, both the BURN and THIN + BURN treatments significantly increased the concentration of NO_3-N compared with the THIN treatment and CONTROL. Compared with the CONTROL, the THIN + BURN treatment increased the concentration of NH_4-N 17-fold, increased the concentration of inorganic N 8-fold, and increased the

Table 2
Post-treatment depth, mass, and C and N status of the forest floor horizons following fuel treatments, adjusted for pre-treatment values using ANCOVA

Soil property	CONTROL	THIN	BURN	THIN + BURN	Model R^2	p
Depth (cm)						
Litter	2.0 a	2.0 a	0.9 b	0.9 b	0.93	***
Duff	3.5 a	3.1 a	0.2 b	0.1 b	0.94	***
Mass (Mg ha^{-1})						
Litter	18.74 a	16.85 a	8.13 b	7.09 b	0.95	***
Duff	52.78 a	45.33 a	2.70 b	1.85 b	0.94	***
Total C (Mg ha^{-1})						
Litter	8.60 a	7.65 a	2.99 b	2.92 b	0.95	****
Duff	19.96 a	16.42 a	0.82 b	0.68 b	0.93	***
Total C (g kg^{-1})						
Litter	470.4 a	472.3 a	372.3 b	381.4 bc	0.82	*
Duff	369.6 a	355.5 a	293.1 b	344.7 ab	0.76	*
Total N (Mg ha^{-1})						
Litter	0.189 a	0.147 ab	0.083 bc	0.062 c	0.93	***
Duff	0.651 a	0.489 a	0.034 b	0.023 b	0.94	***
Total N (g kg^{-1})						
Litter	9.8 a	8.89 a	9.94 a	8.98 a	0.57	ns
Duff	11.20 a	10.80 a	9.67 a	9.81 a	0.86	ns

ns: $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$. Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

inorganic N pool by 27-fold (Table 3). Net nitrification rates in the THIN + BURN treatment were greater than CONTROL, however the differences were not significant ($p = 0.07$). Rates of net N mineralization did not differ significantly among treatments (Table 3).

Soil pH significantly increased in both the BURN and THIN + BURN treatments, relative to the CONTROL and THIN treatments (Table 4). The BURN treatment significantly reduced soil CEC, reducing it by 17% relative to the CONTROL. Base saturation in the THIN + BURN treatment increased 133% relative to the CONTROL, measured as a significant change. Both BURN and THIN + BURN treatments showed significant increases in the concentration of exchangeable Ca compared with the CONTROL treatment.

Average soil bulk density did not differ among the four treatments (Table 4). However, soil strength in the THIN + BURN treatment was significantly greater than in the BURN and CONTROL treatments.

3.3. Skid trails

The presence of skid trails had a strong influence on burn patterns in the prescribed fire treatments. On average, 16% of the BURN treatment did not burn, while 25% of the THIN + BURN treatments remained unburned. Within the BURN treatment, 75% of the area that remained unburned was occupied by skid trails, while in the THIN + BURN treatments, skids accounted for 88% of unburned areas (Table 5). In the BURN and THIN + BURN treatments overall, only 6% of non-skid plots did not burn.

Within treatments, significant differences were observed between soil samples collected from skid trails, compared to samples from non-skid areas. The effects of the prescribed fire

Table 3
Post-treatment C and N status of the mineral soil following fuel treatments, adjusted for pre-treatment values using ANCOVA

Soil property	CONTROL	THIN	BURN	THIN + BURN	Model R^2	p
Total C (g kg^{-1})	54.78 a	52.74 ab	46.89 b	53.01 ab	0.92	*
Total C pool (Mg ha^{-1})	66.41 a	64.22 a	55.79 a	58.50 a	0.80	ns
Total N (g kg^{-1})	2.41 a	2.37 a	2.23 a	2.43 a	0.89	ns
Total N pool (Mg ha^{-1})	2.90 a	2.90 a	2.64 a	2.72 a	0.77	ns
Inorganic N (mg kg^{-1})	4.61 a	1.44 a	17.45 ab	36.42 b	0.86	**
Inorganic N (kg ha^{-1})	1.40 a	2.37 a	22.35 b	38.30 c	0.93	***
NO_3-N (mg kg^{-1})	0.51 a	0.38 a	3.23 b	4.67 b	0.91	***
NH_4-N (mg kg^{-1})	1.91 a	1.27 a	14.83 ab	33.12 b	0.77	*
Net nitrification (mg m^{-2} day^{-1})	2.45 a	7.85 a	13.15 a	16.66 a	0.61	ns
Net N mineralization (mg m^{-2} day^{-1})	5.17 a	12.94 a	8.31 a	17.45 a	0.34	ns

ns: $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$. Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

Table 4
Post-treatment pH, exchange properties, and physical measures of the mineral soil following fuel treatments, adjusted for pre-treatment values using ANCOVA

Soil property	CONTROL	THIN	BURN	THIN + BURN	Model R^2	p
pH	5.19 a	5.26 a	5.83 b	5.81 b	0.97	****
Cation exchange capacity (cmol kg^{-1})	17.47 a	17.39 a	14.51 b	15.45 ab	0.92	*
Base saturation (cmol kg^{-1})	7.20 a	7.71 ab	8.83 ab	9.60 b	0.91	*
Exchangeable Ca (mg kg^{-1})	1.24 a	1.32 a	1.57 ab	1.70 b	0.91	*
Exchangeable Mg (mg kg^{-1})	0.07 a	0.08 a	0.07 a	0.08 a	0.84	ns
Exchangeable K (mg kg^{-1})	0.15 a	0.17 a	0.15 a	0.18 a	0.41	ns
Exchangeable Na (mg kg^{-1})	0.0034 a	0.0040 ab	0.0038 ab	0.0054 b	0.74	*
Soil fine bulk density (g cm^{-3})	0.815 a	0.84 a	0.80 a	0.76 a	0.81	ns
Soil strength (kPa)	975 ab	1016 ab	923 a	1200 b	0.77	*
Exposed bare soil (%)	4 a	6 a	46 b	56 b	0.88	**

ns: $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$. Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

Table 5
Percent of sample area burned, and the influence of skid trails (ave ± S.E.)

Percent of area	BURN	THIN + BURN
Sample area burned	84 (6)	75 (2)
Non-skid area burned	92 (6)	95 (1)
Skid area burned	72 (9)	48 (2)
Non-burned area occupied by skids	75 (15)	88 (4)
Skid area	41 (4)	42 (5)

treatments were far less pronounced in the skid trails. In both the BURN and THIN + BURN treatments, the average pool of soil inorganic N measured in skid trails was less than half and significantly lower than that measured in non-skid areas (Table 6). Still, ANCOVA performed using only skid trail data for the four treatments showed that inorganic N pools in skid trails of the THIN + BURN treatment were significantly greater than skid trails in the CONTROL or THIN treatment (Table 7).

Like inorganic N, increases in soil pH following prescribed fire were moderated within skid trails. Within the BURN and THIN + BURN treatments, soil pH in skid trails was about 0.4–0.7 pH units less than the pH in the non-skid areas (Table 6). ANCOVA analysis using only skid trail data among the four treatments showed that the pH in skid trails of the BURN and THIN + BURN treatments were significantly greater than in skids of the CONTROL or THIN treatments (Table 7). The prescribed burning effects in skid trails increased the pH by about 0.3–0.4 pH units above the pH measured in skid trails of the CONTROL or THIN treatments.

Table 6
Influence of skid trails on soil properties, adjusted for pre-treatment values using ANCOVA

Treatment	Soil property	Skid trail	Non skid trail	p
BURN	Inorganic N (mg kg^{-1})	10.62 a	26.43 b	*
	Inorganic N (Mg ha^{-1})	13.50 a	30.66 b	*
	pH	5.53 a	5.92 b	**
	Exchangeable Ca (kg ha^{-1})	1.62 a	1.97 b	*
THIN + BURN	Inorganic N (mg kg^{-1})	22.85 a	45.81 a	ns
	Inorganic N (Mg ha^{-1})	15.61 a	53.14 b	*
	pH	5.40 a	6.07 b	**
	Exchangeable Ca (kg ha^{-1})	1.40 a	2.11 b	**
	Soil strength (kPa)	2674 a	−225 b	*
THIN	Soil strength (kPa)	1198 a	897 b	*

ns: $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$. Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

In both the mechanically harvested treatments, soil strength, as measured in kPa, was significantly greater in skid trails compared to non-skid areas (Table 6). No differences in soil strength between skid and non-skid areas were found for the CONTROL or BURN treatment. ANCOVA analysis of soil strength in skid trails differed among the four treatments (Table 7). Skid trails in the THIN + BURN treatment had significantly greater soil strength than in all other treatments, and skid soil strength in the THIN treatment was greater than in BURN.

4. Discussion

4.1. Forest floor

Fuel treatments that included prescribed fire reduced both the depth and mass of the forest floor by consuming litter and duff materials. Compared to the CONTROL, the combined depth of litter and duff was reduced by more than 80% in both the BURN and THIN + BURN treatments (Table 2). Although these treatments produced essentially the same residual litter and duff thickness, the THIN + BURN treatment consumed more fuels because harvest slash and masticated woody material had been added to the forest floor prior to burning, as part of the mechanical treatment. Relative to the CONTROL, C losses in the organic horizons averaged 25 Mg C ha^{-1} in the BURN and THIN + BURN treatments (Table 2). The C losses in this study are slightly greater than those reported for other prescribed fires in the Sierra Nevada. For example, Caldwell et al. (2002) reported C losses of 6–24 Mg C ha^{-1}, however their study site is located in the semiarid forests of the eastern Sierra Nevada. The forest floor reduction and concomitant loss of C in the organic horizons at our study site is far greater than what was observed at another FFS installation in western Montana. Gundale et al. (2005) reported 13–17% consumption of duff, with decreases of organic horizon C ranging from 3 to

Table 7
Select chemical and physical treatment effects within skid trails, adjusted for pre-treatment values using ANCOVA

Soil property	CONTROL	THIN	BURN	THIN + BURN	Model R^2	p
Skid inorganic N (Mg ha^{-1})	1.89 a	2.13 a	12.53 ab	19.26 b	0.78	*
Skid pH	5.10 a	5.19 a	5.54 b	5.46 b	0.94	***
Skid soil strength (kPa)	1134 ab	1302 b	1039 a	1640 c	0.95	***

ns: $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$. Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

5 Mg C ha^{-1} relative to the CONTROL in their ponderosa pine/Douglas-fir forest. The Montana FFS site conducted spring burns, which often result in less severe fire behavior due to increased moisture content of the forest floor and mineral soil compared to fall burns.

The prescribed fire treatments in our study significantly reduced the nutrient pools stored in the litter and duff layers. Relative to the CONTROL values, the BURN and THIN + BURN treatments resulted in total N losses from the forest floor of 86 and 90%, or 0.72 and 0.76 Mg N ha^{-1}, respectively (Table 2). These losses are higher than those reported for prescribed fire treatments in Jeffrey pine forests of the eastern Sierra Nevada (Murphy et al., 2006), and ponderosa pine forests of northern Arizona and central Oregon (Klemmedson, 1976; Nissley et al., 1980; Covington and Sackett, 1984). However, they are within the range of N losses following prescribed burning of logging slash in northern coniferous forests (Feller, 1989; Beese, 1992). In contrast, the Montana FFS site found no significant differences in forest floor N among the four treatments.

Of the total N pool stored in the forest floor and upper mineral soil of the CONTROL treatments, about 22% is stored in the former, and 78% in the latter. Compared with the CONTROL, the 37 kg N ha^{-1} increase in mineral soil inorganic N in the THIN + BURN only represents 5% of the 755 kg N ha^{-1} lost from the forest floor (Tables 2 and 3). While this large increase of available N to the mineral soil will likely enhance site productivity (Covington and Sackett, 1992), the large N reserve found in the forest floor has been depleted. Large accumulations of forest floor and surface fuels were probably not supported under the historic fire regime at our site. At the 3–5-ha scale, Stephens and Collins (2004) measured the median composite fire return interval in our project area as 6–14 years, with a fire interval range of 4–28 years. Hazardous fuel accumulations increase the risk of high severity fires, which may have longer-term effects on soil N status than more frequent prescribed fires (DeLuca and Zouhar, 2000).

While a substantial amount of litter and duff was consumed by the prescribed fire treatments, litterfall from scorched branches provided new litter inputs almost immediately after the burns were completed, and following fall and winter storms. Fresh litter generally has higher C concentrations than older residues. As decomposition of a substrate proceeds, C is released by respiration. However, litter C concentrations in the BURN and THIN + BURN treatments were lower than CONTROL litter. In addition, the C concentration of the duff layer in the BURN treatment was also lower than the CONTROL duff. Partial combustion and volatilization of these organic materials may have resulted in the lowered C concentrations. There were no significant differences in total N concentrations in litter or duff among treatments. Concentrations of total N and C did not behave similarly, although both N and C volatilize at relatively low temperatures (Raison et al., 1985). While N losses occur at a threshold temperature of 200 °C (Knight, 1966; Neary et al., 1999), substantial organic matter can be lost at 100 °C (Hosking, 1938). The reduced C concentrations may be an artifact of the samples collected. Pre-treatment samples consisted of unburned organic matter, while post-burn samples also contained scorched materials and ash. Concentrations were determined on a weight basis, and may have changed due to the changed nature of the base material (Knight, 1966; Knoepp et al., 2005).

4.2. Mineral soil

In addition to the organic horizons, the BURN treatment significantly reduced the concentration of total C in the mineral soil relative to the CONTROL treatment (Table 3). Combustion occurs in three phases—flaming, smoldering, and glowing (DeBano and Neary, 2005). Extended periods of glowing combustion, in particular the burnout of stumps and downed wood, can lead to greater soil heating and loss of soil C. Both the BURN and THIN + BURN treatments consumed stumps and coarse woody debris (CWD) on the forest floor. When all CWD decay classes were pooled, the BURN treatment significantly reduced the volume of coarse woody debris present on the forest floor, while the CWD in the THIN + BURN treatments did not significantly differ from the other treatments (Stephens and Moghaddas, 2005a). With greater consumption of CWD in the BURN treatment, more heat was transferred into the soil, and more soil C was lost. While the THIN + BURN treatment burned with higher severity and had longer periods of flaming combustion than the BURN treatment (Stephens and Moghaddas, 2005b), the total soil C in the THIN + BURN did not significantly differ from the CONTROL. Glowing combustion of stumps and large wood can last from hours to days, and have profound effects on soil heating and chemical alteration. Flaming combustion at the fire front, however, may last only several minutes, and can be a misleading indicator of belowground effects.

Despite the dramatic loss of forest floor N, total mineral soil N concentrations and pools did not differ among treatments (Table 3). As expected, the inorganic N fraction increased following the prescribed fires (Raison, 1979; DeBano et al., 1998; Knoepp et al., 2005). The magnitude of the increases was much greater than expected, however. The THIN + BURN treatment had the greatest impact on soil available N. Concentrations of NH_4-N increased by 31 mg N kg^{-1} (1734%) above the CONTROL (Table 3). Increases in NH_4-N between 16 and 43 mg N kg^{-1} have been reported during medium and high severity fires, respectively (Knoepp et al., 2005). Smithwick et al. (2005) reviewed soil NH_4-N increases in prescribed fires and wildfires from both surface and stand-replacing fires. The highest increases in conifer forests (2349% above control values) were found following prescribed fire in southwest old growth ponderosa pine (Covington and Sackett, 1992). This percent increase corresponded to an NH_4-N increase of 43 mg N kg^{-1}. In our BURN treatment, NH_4-N increased 776% above the CONTROL (Table 3). Despite this large increase in mean value, the BURN NH_4-N concentration was not statistically different than the CONTROL.

While burning can oxidize and decompose organic matter to release highly available NH_4, N in the form of NO_3 is generated by the nitrification of NH_4. The prescribed fire treatments significantly increased the concentrations of soil NO_3-N (Table 3). Due to the high levels of available NH_4, we assume that nitrifying organisms in the BURN and THIN + BURN treatments converted some of this into NO_3. Net nitrification rates in the THIN + BURN treatments were greater than CONTROL ($p = 0.07$). Increases in both NH_4 and NO_3 are expected to be relatively short lived. Our sampling occurred about 8 months following the prescribed fire treatments. Other studies report that inorganic N returns to pre-treatment levels within several years (DeLuca and Zouhar, 2000). The high levels of available N adds to the fertility of the site. This N is also susceptible to leaching losses down the soil profile.

Soil pH typically increases following fire due to hydrolysis of base cation oxides contained in ash (Raison, 1979; Ballard, 2000; Korb et al., 2004). In our study, a significant increase in pH was measured in the BURN and THIN + BURN treatments compared to THIN and CONTROL (Table 4). In the burned treatments, pH was elevated by about 0.6 pH unit above the CONTROL. In contrast, no significant differences in soil pH were detected at the Montana FFS site (Gundale et al., 2005). Although ash is typically rich in Ca, Mg, K, Na, at our site significant increases in exchangeable cations were only measured for Ca and Na, and only in the THIN + BURN treatments. Concentrations of exchangeable Ca and Na in the BURN treatment were intermediate between the CONTROL and THIN + BURN, and were not significantly different than either. A confounding factor may be that the CEC in the BURN treatment was significantly lower than the THIN and CONTROL. We suspect that the reduction in soil C in the BURN treatment resulted in reduced CEC, which would limit cation retention. Base saturation in the THIN + BURN was significantly greater than THIN and CONTROL but, surprisingly, base saturation in the BURN treatment did not differ from other treatments.

No significant differences in soil bulk density were detected among treatments (Table 4). However, average soil strength was significantly higher in the THIN + BURN treatment compared to the BURN treatment. All treatment units are part of a managed forest and have been impacted by commercial timber harvests. While the mechanically harvested treatments have had more recent impacts from logging equipment, their effects on soil compaction were ostensibly diluted when mean treatment effects were determined.

4.3. Influence of skid trails

The presence of skid trails moderated fire effects on soil properties. Before the prescribed fire treatments, the skid trails generally supported less fuel, with reduced fuel continuity compared to the undisturbed portions of each unit. In the BURN and THIN + BURN treatments, 75 and 88% of unburned areas, respectively, were occupied by skid trails (Table 5). While all treatment units had been harvested in the past and contained skid trails, skids in the more recently harvested (THIN + BURN) units had more exposed bare soil and supported a lower quantity of fuels prior to being burned. As a result, more of the unburned areas were occupied by skid trails. In comparison, 92 and 95% of non-skid areas, in BURN and THIN + BURN treatments, respectively, showed evidence of burning.

In both BURN and THIN + BURN treatments, soil inorganic N, pH, and exchangeable Ca were significantly lower in skid trails compared to the non-skid areas (Table 6). To determine if treatment effects were detectable solely in the skid trail areas, we conducted ANCOVA analyses using only data from skid trails. Inorganic N pools in the THIN + BURN skid trails were significantly greater than those in skid trails of the CONTROL or THIN treatment (Table 7). Soil pH in skid trails of the BURN and THIN + BURN treatments were significantly greater than skid trails in the CONTROL or THIN treatment. Although the effects of prescribed fire on soil chemistry were reduced in skid trails compared to the non-skid areas, the skid trails still exhibited chemical changes as a result of fire. Considering that such a high proportion of skid trails did not burn, it is surprising that the averaged skid trail data reflects significant changes in soil chemistry compared to skid trails in the non-burn treatments.

Because such a high proportion of undisturbed areas burned, we used these samples to better assess the effects of fire on soil properties. In addition to the overall treatment effects described above, average values for all soil measures were also determined based solely on the undisturbed, non-skid areas. ANCOVA and Tukey's HSD were used to examine differences between treatments for these values. For many variables, significant differences among treatment effects (significantly increased, decreased, or no change) were the same for the non-skid data as the whole treatment results (data not shown).

All stands had been treated with at least one harvest entry (commercial thin from below) prior to the fire and fire surrogate treatments examined in this study. However, differences in soil strength between skid trails and non-skid areas were only detected in the mechanically harvested treatments. Relative to the non-skid areas, soil strength in skid trails was increased by an average of about 300 and 2900 kPa in the THIN and THIN + BURN treatments, respectively (Table 6). An increase in soil strength as a result of compaction can inhibit plant root growth (Whalley et al., 1995; Gomez et al., 2002). To minimize the impacts of skid trails, some management agencies impose limitations on the percentage of the harvest area that can be occupied by skid trails (Harvey and Brais, 2002). Although compaction can affect soil physical properties for decades (Wert and Thomas, 1981), no significant differences in soil strength were found between skid trail and non-skid areas of the CONTROL or BURN treatments. Prior harvests in these treatment units occurred between 4 and 7 years before this sampling. This suggests that the increase in soil strength is possibly temporary, and may not be detectable in several years.

5. Conclusion

This research was designed to compare an untreated control and fuel reduction treatments that (1) modify forest structure through mechanical manipulation, (2) reintroduce fire as an ecosystem process, or (3) incorporate both structure- and process-based management tools. Our findings suggest that, in the short term (1–2 years following treatment), the THIN treatment had the least effects on soil chemical and physical properties. By using ANCOVA and Tukey's HSD to compare the four treatments, there were no significant differences between the structure-based THIN treatment and the untreated CONTROL for the variables discussed in this paper.

The prescribed fire treatments both produced dramatic yet similar changes in soil properties. More than 80% of the forest floor was consumed by fire, leaving a significantly reduced depth and mass of litter and duff. As a result, 25 Mg C ha^{-1} and more than 700 kg N ha^{-1} stored in the organic horizons were lost or relocated, and bare soil was exposed on nearly 50% of the treatment areas. The BURN and THIN + BURN treatments both raised soil pH by 0.6 pH units and inorganic N levels were increased to 4–8 times the CONTROL value. The BURN treatment had a greater impact on soil C resources, reducing both the C concentration and CEC of the mineral soil. The THIN + BURN treatment, in contrast, had a greater impact on available soil N, dramatically increasing both the concentrations and pools of inorganic N. However, this increase in soil N represents only 5% of the N lost from the forest floor. The remaining 95% may have leached deeper in the soil profile or been transported off site.

Although these fires burned within the prescribed weather and fuel moisture conditions, these effects on soil resources are severe. Surprisingly, the large losses in forest floor C and N were not reflected in the mineral soil, where total C and N pools did not significantly differ among the four treatments. Due to the increased levels of available N in the mineral soil, site productivity is expected to be enhanced in the short term. Historically, fire was a frequent disturbance agent in these forests, with a median composite fire return interval of 6–14 years (Stephens and Collins, 2004). The last recorded fire occurred in the area in 1900. In the absence of fire, the fuel load and nutrient pool in the forest floor has likely increased during the 20th century. While the prescribed fire treatments in this study were conducted during the same late-season period in which historic fires occurred, due to the high levels of fuel consumption the impacts to the soil resource are likely outside the historic range of effects.

Previous management activities contributed to the heterogeneity of the burn treatments and subsequent soil effects. Skid trails and soil disturbance caused by harvest equipment modified the quantity and continuity of ground and surface fuels. Skid trails moderated the effects of prescribed fire treatments, resulting in increased spatial heterogeneity. Densities of trails used by skidding and forwarding equipment in managed forests often range from 10 to 40% of the harvest area (Turcotte and Smith, 1991; Stokes et al., 1995; Ficklin et al., 1997; Buckley et al., 2003; Dwyer et al., 2004; Murphy et al., 2006). While local weather, topography and fuels dictate fire behavior, the skid network and soil disturbance due to harvest equipment may also be a main component in the spatial heterogeneity of fire effects. In light of the current management emphasis on hazardous fuels reduction, we recommend that researchers investigating fire effects in harvested stands include skid trail influences in their study design.

Acknowledgments

This is contribution number 131 of the National Fire and Fire Surrogate Project, funded by the US Joint Fire Sciences Program. We are grateful to the staff of the University of California Blodgett Forest Research Station for their dedicated cooperation and support of the Fire and Fire Surrogate Study. We thank Jason Moghaddas for reviewing early versions of this manuscript, for his field and laboratory assistance, and for his devotion to this project.

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