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Recovery of small pile burn scars in conifer forests of the Colorado Front Range

Charles C. Rhoades [a,*], Paula J. Fornwalt [a], Mark W. Paschke [b], Amber Shanklin [b], Jayne L. Jonas [b]

[a] US Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80526, United States
[b] Forest and Rangeland Stewardship Department, Colorado State University, Fort Collins, CO 80523-1472, United States

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ABSTRACT

The ecological consequences of slash pile burning are a concern for land managers charged with maintaining forest soil productivity and native plant diversity. Fuel reduction and forest health management projects have created nearly 150,000 slash piles scheduled for burning on US Forest Service land in northern Colorado. The vast majority of these are small piles (<5 m diameter). Similar to larger piles, we found that burning small piles had significant immediate effects on soil nutrients and physical and chemical properties and native plant cover. To evaluate the need to rehabilitate small piles and compare the effectiveness of treatment options, we examined soil and plant responses to treatments designed to alter soil nutrients, moisture and temperature and to increase seed availability. We compared four surface treatments (soil scarification, woodchip mulch, tree branch mulch, untreated scars), with and without addition of a native seed mixture. Natural recovery and treatment effects were examined for 2.5 years after pile burning at 19 conifer forest sites along the Colorado Front Range. Woodchip mulch had dramatic effects on soil moisture, temperature, decomposition and inorganic soil N compared to the other treatments, untreated scars or unburned areas; woodchip mulch also suppressed plant establishment. Seeding increased total native species richness as expected, but had marginal effects on forb cover and no effect on graminoid cover. Soil N availability and plant cover did not differ from unburned areas in the absence of surface or seeding treatments within two years of pile burning. Neither reduced seed availability nor altered soil properties following burning hindered revegetation of these small burn scars by native herbaceous plants. Our findings indicate that rehabilitation may not be required for small burn pile scars except in sensitive areas, such as those with water quality and invasive plant concerns.

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1. Introduction

Slash burning has long been used to reduce wildfire risk and surface fuel loads after harvesting and fuel reduction treatments in western North American forests (Isaac and Hopkins, 1937; McCulloch, 1944). Accumulating and burning logging slash and non-merchantable woody material in piles has effects on vegetation and soils that are typically more severe than those of either wildfire or broadcast burning (Ahlgren and Ahlgren, 1960; DeBano et al., 1998; Wan et al., 2001; Certini, 2005). Extreme temperatures that penetrate soil beneath burning slash piles can destroy seed reserves and plant tissues and alter physical, chemical and biological soil properties (Busse et al., 2010). The immediate effects of pile burning on soil microbes, acidity, organic matter and plant nutrients (Tarrant, 1956; Covington et al., 1991; Wan et al., 2001) and longer-term effects relating to loss of aggregate structure, decreased water infiltration, and mineralogical and color changes (Dyrness and Youngberg, 1957; Debano and Rice, 1973; Ulery et al., 1993; Busse et al., 2010; Rhoades and Fornwalt, 2015) have been documented for more than a half century. More recently, elevated nutrients, altered water relations and exposed soil surfaces of pile burn scars have been shown to favor non-native plant establishment (Haskins and Gehring, 2004; Korb et al., 2004; Creech et al., 2012) and threaten surface water quality (Johnson et al., 2011). Though its effects are well-characterized, few studies have examined the need to actively rehabilitate burn scars to facilitate community and ecosystem recovery.

Organic mulches and other amendments and treatments are commonly used to try to rehabilitate soils, speed native plant recovery and limit weedy plant establishment after pile burning. Such treatments have been shown to ameliorate seedbed temperature and soil moisture extremes, restore soil nutrients and the microbial processes that regulate them, and replace lost seed reserves (Korb et al., 2004; Fornwalt and Rhoades, 2011; Creech

* Corresponding author.
E-mail address: crhoades@fs.fed.us (C.C. Rhoades).

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et al., 2012). Native understory plant cover was increased within burn scars in Arizona ponderosa pine forests and that of non-native and ruderal species was reduced by addition of topsoil containing mycorrhizal spores (Korb et al., 2004). Woodchip mulch has been shown to reduce the elevated levels of inorganic soil N that follow pile burning (Fornwalt and Rhoades, 2011) and may also increase soil moisture and dampen soil temperature fluctuations (Rhoades et al., 2012). Scarification to disrupt sealed surface soils and hydrophobic layers has potential to enhance water infiltration and revegetation of areas affected by burning (Robichaud et al., 2000; Fornwalt and Rhoades, 2011). The previous studies document that seeding combined with surface amendments increased plant establishment more than surface or seeding treatments alone (Korb et al., 2004; Fornwalt and Rhoades, 2011). However, burn scar rehabilitation may not be economically feasible or ecologically necessary in all conditions; the need for rehabilitation and appropriate treatments are likely to vary with pile size and management objectives.

Fuel reduction and forest health management activities on US Forest Service land in northern Colorado alone have created >140,000 piles scheduled for burning (USFS, 2010) and thousands of additional piles have been created on county, state and National Park Service lands. Most of these were small hand-built or machine-built piles (<5 m diameter) that can cover considerable portions (>15%) of treatment areas (Busse et al., 2013). Federal regulations (National Forest Management Act of 1976; US P.L. 94-588) stipulate that management activities must not permanently degrade the productive capacity of soils and Best Management Practices (US Forest Service, 2006) prescribe active rehabilitation where soil damage is severe or exceeds 15% of a treated area (US Forest Service, 2006). However, despite their high numbers and common occurrence along roads and stream corridors, small burn scars have not typically been rehabilitated.

Simple, low-cost treatments aimed at rehabilitating exposed, fire-altered soils and establishing native plants may be relevant to fuels and forest management efforts in conifer forests of northern Colorado and throughout western North America. Managers confronted with a surplus of small, slash piles must consider whether to actively rehabilitate burn scars or allow natural processes to restore them. To inform this decision, we first characterized the consequences of burning small slash piles and then compared soil and plant responses to surface rehabilitation and seeding treatments. We measured soil temperature and moisture, inorganic soil nitrogen, microbially-mediated decomposition and plant cover and species diversity to assess if the treatments were effective at ameliorating soil and seedbed conditions. This work will help determine if rehabilitation is worthwhile to facilitate recovery of small burn scars within 3 years of pile burning.

2. Methods

2.1. Study sites and rehabilitation treatments

The study was established at twenty hazardous fuel treatment project sites distributed along a 90 km latitudinal band of the northern Front Range, west of Boulder and Fort Collins, Colorado, USA (39°56′N to 40°45′N). The sites, which were located on US Forest Service (Arapaho-Roosevelt National Forest) and Boulder County Open Space land, ranged in elevation from 2214 to 2772 m (see on-line map). Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are dominant overstory species at lower elevations (2200–2600 m) and lodgepole pine (*Pinus contorta*) is dominant at higher elevations (above 2700 m). Annual precipitation averages 440 and 385 mm for climate stations located near the southern and northern extent of the study area (WRCC, 2013). January minimum temperatures average −9.2 °C and −11.2 °C and July maximum temperatures average 26.3 °C and 24.6 °C within the study area. The northern Front Range is underlain by crystalline, granitic and metamorphic bedrock that weathers into coarse-textured soils. In general, soils at the study sites are classified as loamy skeletal Eutrocryepts, Dystrocryepts and Haplustalfs (NRCS, 2013a).

Slash piles at the study sites were created from canopy and ladder fuels harvested in 2006 and 2007. The resulting biomass was hand-piled and burned during winter 2008/2009 at all sites. The twenty study locations represented the range of forest, soil and site topography typical of Front Range conifer forests. Within a given site, we selected ten burn scars that had similar size, shape, surrounding vegetation and burn severity (estimated from consumption of woody fuel) during summer 2009. Burn scars spanned 2.1–5.4 m in diameter (3.5 m mean).

Surface (untreated control, hand scarification, branch mulch, and woodchip mulch) and seeding treatments (with and without the addition of native plant seeds) were randomly assigned in a factorial experimental design in summer 2009, with each treatment combination replicated once per site (Fig. S1). The scarification treatment was conducted using a McLeod fire tool to till the upper 10 cm of the fire scar; the surface was left roughened. Woodchips were created on-site and applied in a ~10 cm mulch layer; chip pieces were relatively uniform (~2–10 cm long by 1–2 cm thick). The mulch application depth was based on previous research in Front Range conifer forests that showed more consistent reductions in soil N availability under thicker mulch (15 vs 7.5 cm) (Rhoades et al., 2012). Tree branches from forest thinning operations were placed on the fire scars to create approximately 50% shade on the branch mulch treatment based on hand-held light meter measurements. Seeded piles received a mixture of 32 species native to conifer forests of Colorado's northern Front Range (Table S2). Plants included 20 species of annual, biennial, or perennial forbs, 10 perennial grass species and 2 perennial shrub species. Seeds were hand-collected from local populations or purchased from regional suppliers. All hand-collected seed was tested for purity and germination at the Colorado State University Seed Laboratory. The mixture was hand-broadcast at a rate of 2700 pure live seeds m^{-2} with forbs added at approximately 3 times the rate of grasses. A garden rake was used to roughen a 1 cm seedbed prior to seeding. Burn scars were seeded after scarification but prior to mulching. Soil was tamped with a McLeod to improve seed to soil contact after seeding.

2.2. Soil and plant sampling and analysis

We examined the initial effects of pile burning on soils in 2010 (1.5 years after burning) and on plants in 2010 and 2011 (1.5 and 2.5 years after burning) at two untreated scars per site. The 2010 sampling was conducted at twenty fuel reduction project sites; a fall 2010 wildfire eliminated one site from subsequent sampling. To gauge burn effects we sampled the interior of each burn scar, a 0.5 m band inside the scar perimeter, and the unburned area adjacent to each scar, 2 m beyond the scar perimeter. It was not possible to differentiate the edge zone once surface treatments were established (2009), so treatment comparisons were made for the interior zone only (2010 and 2011).

We compared soil physical and chemical properties by scar zone for untreated pile burn scars. Soil hydraulic conductivity was determined using a field infiltrometer designed to assess wildfire effects (Decagon Devices, Pullman, WA). We recorded the volume of water infiltrating during 60 s periods (2 subsamples per scar zone). We assessed soil aggregate stability using a qualitative slaking assay on 1–2 cm diameter aggregates (Herrick et al., 2001) collected from the upper 5 cm of mineral soil (6 subsamples per scar zone). Mineral soil (0–10 cm depth) was sampled by scar zone, air dried, passed through a 2 mm sieve, ground and analyzed for total C and N by dry combustion (LecoTru-Spec, Leco Corp., St. Joseph, MI). Mineral soil pH (0–10 cm depth) was measured in 1:1 mixture of soil and 0.01 $\underline{M}$ $CaCl_2$ (Thomas, 1996) using a temperature-corrected glass electrode (Accumet Model 50, Thermo Fisher Scientific Inc., Pittsburgh, PA).

We estimated the effects of pile burning and of rehabilitation treatments on plant-available soil nitrogen using ion exchange resin (IER) bags (Binkley and Matson, 1983). Resin bags were inserted in mineral soil at 5–10 cm depth in a zone of high root density and microbial activity and exchanged each spring and fall during 2010 and 2011. Resin bags consisted of a 1:1 mixture of cation (Sybron Ionic C-249, Type 1 Strong Acid, Na form, Gel Type) and anion (Sybron Ionic ASB-1P Type 1, Strong Base OH form, Gel Type) exchange resin beads. After removal from the field, resins were extracted with a 2 $\underline{M}$ KCl solution, shaken for 60 min, filtered and frozen until analysis. Nitrate and ammonium concentrations were measured using a Lachat QuickChem 7000 Flow Injection Analyzer (Latchat Company, Loveland, CO).

We assessed the effects of rehabilitation treatments on soil moisture by measuring volumetric soil water content (0–10 cm depth) during May and September of 2010 and 2011 with a hand-held, time domain reflectometry probe (CD 620, HydroSense Campbell Scientific, Logan, UT). Duplicate soil water measurements were collected and composited by scar zone. Soil temperature (10 cm depth) was measured continuously throughout 18 months (Onset Computer Corp., Pocasset, MA) in the interior of treated burn scars at one study site.

We compared how surface treatments influenced decomposition of three substrate types (alfalfa C:N = 16:1; hardwood medical examination sticks C:N = 500:1; analytical grade, cellulose filter paper; Ratliff, 1980). Plastic mesh litterbags containing dried, pre-weighed material were secured to the soil surface. Litterbags were removed after one year and the remaining material was dried at 55 °C to a constant weight. Subsamples of substrate were ground and combusted for four hours at 550 °C and reweighed to determine ash-free content of material remaining in the litterbags.

Pile burning and rehabilitation treatment effects on plant, mineral soil, litter, and rock cover were evaluated with a gridded point-intercept method in 0.25 × 0.75-m sample quadrats. Sampling was conducted in August 2010 and 2011 and quadrat locations were shifted each year to avoid areas altered by previous sampling. Species richness was defined as the number of live species per quadrat. Plant nativity was classified according to the Plants Database (NRCS, 2013b).

We analyzed pile burning effects on soil and plant attributes by comparing the interior, edge and exterior zones using a mixed model analysis of variance with scar zone as a fixed effect, study site as a random effect and repeated measures for multiple year comparisons (SPSS V. 22, IBM CO, Chicago, IL). Surface and seeding effects were assessed in burn pile interiors in 2010, two years after establishing the treatments using a mixed model analysis of variance approach with surface and seeding treatments as fixed effects and study site as a random effect. Transformations were used when they corrected normality or unequal variance. Statistical significance is reported where $\alpha < 0.05$ except where noted, and post hoc means comparisons were made on Bonferroni-adjusted p values.

3. Results

3.1. Effects of pile burning

Pile burning altered chemical, nutrient, and physical attributes of soils within burn scars compared to unburned adjacent areas

Table 1
Effect of pile burning on soil properties at 20 Colorado Front Range conifer forest sites (0–10 cm depth). Data are means (standard errors) for unseeded, untreated pile burn scars and adjacent, unburned areas 1.5 years after burning. Significant differences among pile burn zones are identified using analysis of variance. Similar letters indicate that means do not differ among zones ($p < 0.05$).

Pile burn zone	pH		Total C (%)		Total N (%)		IER-ammonium (mg N bag^{-1} day^{-1})		IER-nitrate (mg N bag^{-1} day^{-1})		Infiltration (mL min^{-1})		Aggregate stability class	
Interior	6.1	(0.18)a	2.8	(0.23)b	0.13	(0.01)b	10.9	(1.83)a	13.5	(6.65)a	4.8	(0.51)c	2.8	(0.34)b
Edge	5.6	(0.18)b	4.5	(0.33)a	0.18	(0.01)a	2.0	(0.67)b	5.6	(1.63)ab	7.2	(0.54)b	4.3	(0.24)a
Exterior	4.8	(0.08)c	4.1	(0.25)a	0.18	(0.01)a	1.4	(0.43)c	3.0	(0.57)b	9.9	(0.86)a	4.6	(0.22)a
ANOVA results	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p**	*F*	*p**	*F*	*p*	*F*	*p*
	21.49	<0.001	10.07	<0.001	6.93	0.002	35.92	<0.001	4.26	0.019	15.15	<0.001	12.3	<0.001

* Analysis of variance on log-transformed data.

Table 2
Effect of pile burning on soil and native plant cover (%) at 19* conifer forest sites along the Colorado Front Range. Data are means (standard errors) in unseeded, untreated pile burn scars and adjacent, unburned areas. Significant differences among pile burn zones and years were identified using repeated measures analysis of variance on arcsine transformed data. Similar letters indicate that arcsine transformed means did not differ among zones and years (Bonferroni adjusted $p < 0.05$).

	Year	Bare Soil		Litter		Forbs		Graminoids		Shrubs		Total plants	
		%											
Interior	2010	70.6	(5.6)a	9.6	(2.5)b	6.5	(3.6)	5.4	(2.9)	0.3	(0.3)b	12.3	(4.5)b
	2011	49.8	(7.3)b	17.7	(4.9)b	13.2	(4.3)	14.2	(7.2)	0.2	(0.2)b	28.0	(7.5)ab
Edge	2010	31.4	(4.6)bc	33.8	(4.0)a	10.1	(2.7)	9.9	(4.7)	1.0	(0.4)b	21.0	(4.8)ab
	2011	24.5	(3.5)c	35.8	(4.8)a	10.6	(2.3)	18.7	(5.4)	2.4	(1.4)b	31.6	(5.7)a
Exterior	2010	6.0	(2.8)d	49.7	(6.4)a	11.3	(2.6)	9.6	(4.1)	14.7	(4.5)a	36.5	(6.7)a
	2011	6.4	(4.1)d	43.0	(4.4)a	11.5	(3.0)	11.2	(3.1)	13.7	(4.2)a	38.1	(5.4)a
ANOVA results		*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
	Zone	59.9	<0.001	27.9	<0.001	0.6	0.550	1.2	0.307	18.6	<0.001	4.16	0.023
	Year	8.7	0.005	0.1	0.767	2.8	0.098	11.3	0.001	0.0	0.826	13.82	<0.001
	Zone * Year	5.7	0.006	2.0	0.144	1.8	0.179	1.1	0.351	0.0	0.977	3.05	0.056

* One site was removed from the study after it was disturbed in October 2010 by a wildfire.

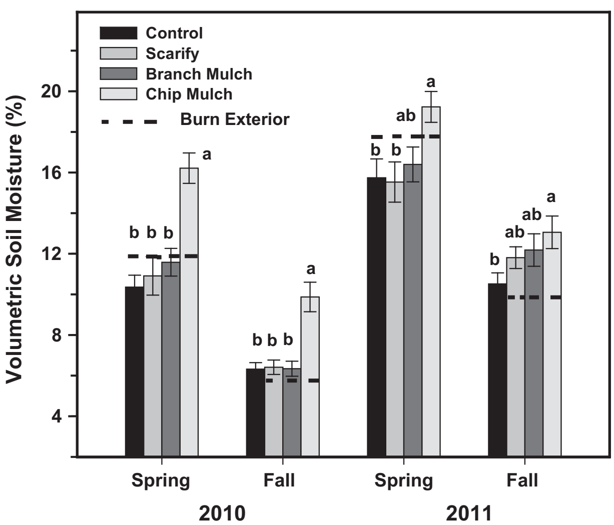

Fig. 1. Surface treatment effects on volumetric soil moisture (0–10 cm depth) in the interior of treated and untreated pile burn scars, measured during spring (May) and fall (September) with a time domain reflectometry probe. Bars show mean and standard error for eight sites. Similar letters indicate that treatment means did not differ within seasonal sampling periods (Bonferroni adjusted $p < 0.05$). The dotted reference lines show mean soil moisture for unburned exterior areas.

(Table 1). For several variables, soils located at the perimeter of burn scars were similar to pile exteriors. Burning increased soil pH in the interior and edge zone; it was 1.3 and 0.8 units higher than unburned areas, respectively, 1.5 years after pile burning. Soil total C and N were 2.8% and 0.1% in scar interiors compared to 4.1% and 0.2% in unburned exteriors. This was equivalent to 19.8 and 1.7 kg ha^{-1} losses of C and N from the top 10 cm of mineral soil using the average bulk density (1.3 g cm^{-3}) measured at the study areas. Pile burning reduced the stability of soil aggregates and the rate of water infiltration in scar interiors relative to soil in unburned areas or the perimeter of burn scars.

Inorganic soil N, indexed by ion exchange resins (IER), was significantly higher within pile burn scars compared to adjacent areas. IER ammonium, nitrate, and the sum of these forms were 7.7-, 4.5- and 5.6-times higher in burn scar interiors relative to surrounding unburned areas (Table 1). Nitrate comprised 68% of total IER-N in unburned soils but only 55% of that measured in scar interiors. IER ammonium and nitrate of burn scar edges were intermediate between interior and exterior zones.

Pile burning also altered soil surface, shrub and total native plant cover (Table 2). Similar to a high severity wildfire, pile burning consumed the majority of organic soil horizons (litter) and exposed mineral soil in the interior of scars. In contrast, litter cover was 3 times higher in the edge zone relative to scar centers; bare mineral soil cover in scar edges was less than half that of the interior zone. One year after burning, total native plant cover in scar interiors was about 30% of that measured in unburned exteriors (Table 2). Shrubs were abundant in the unburned exterior with roughly equivalent cover of forbs and graminoids; shrubs were nearly eliminated by pile burning. Native graminoid and forb cover doubled in the interior of untreated scars the second year after burning resulting in no difference between burn scar zones and unburned exterior. Exotic species cover was <2% over the course of the study and was unaffected by pile burning.

3.2. Effects of surface and seeding treatments

Surface treatments changed volumetric moisture (Fig. 1) and temperature (Fig. 2) of the upper 10 cm of mineral soil. Soil moisture was significantly higher beneath woodchip mulch compared to untreated scars and unburned exterior during both spring and fall seasons (Fig. 1). Untreated scar interiors had lower soil moisture than exteriors zones during spring conditions. Woodchip and branch mulch decreased summer time maximum temperatures and daily fluctuations compared to the untreated scar (Fig. 2); summer soil temperature maxima were 10–15 °C cooler for these treatments relative to the untreated scar. Winter time soil temperature minima were 2–7 °C warmer in woodchip mulched scars; this mulch treatment cooled average summertime soil temperatures 3–4 °C and warmed it by an equal amount during winter months. The woodchip mulch delayed the onset of spring warming for more than a month.

Woodchip mulch consistently reduced both IER-N forms compared to untreated scars (Fig. 3), to levels that were generally below the other surface treatments. For example, during summer 2010 IER-nitrate more than doubled compared to the previous sample period in untreated and treated scars, except those receiving woodchip mulch where it was similar to unburned areas. Scarification and branch mulch lowered IER-ammonium compared to untreated burn scars the first year and a half after treatment, and branch mulch reduced IER-nitrate the second year. Decomposition mass loss varied among substrate types but was consistently highest for woodchip mulched scars (Fig. 4). Filter paper resisted decay in unburned exterior areas, but this substrate nearly disappeared from woodchip mulched scars (>90% mass loss).

Woodchip mulch suppressed native forb and graminoid cover in scars, but neither scarification nor branch mulch had any effect

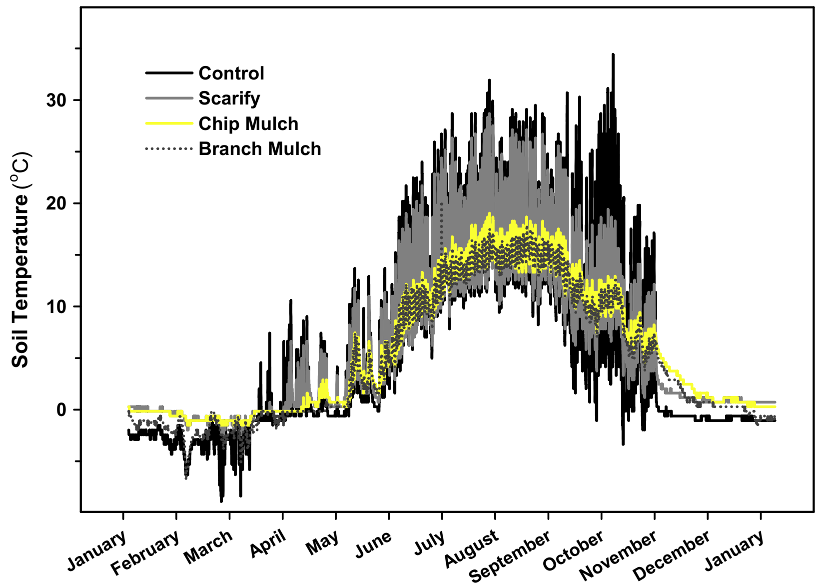

Fig. 2. Soil temperature (10 cm depth) for the interior of pile burn scars at one site in the Colorado Front Range. Data shows temperature recorded at 10-min intervals from January 2011 to January 2012.

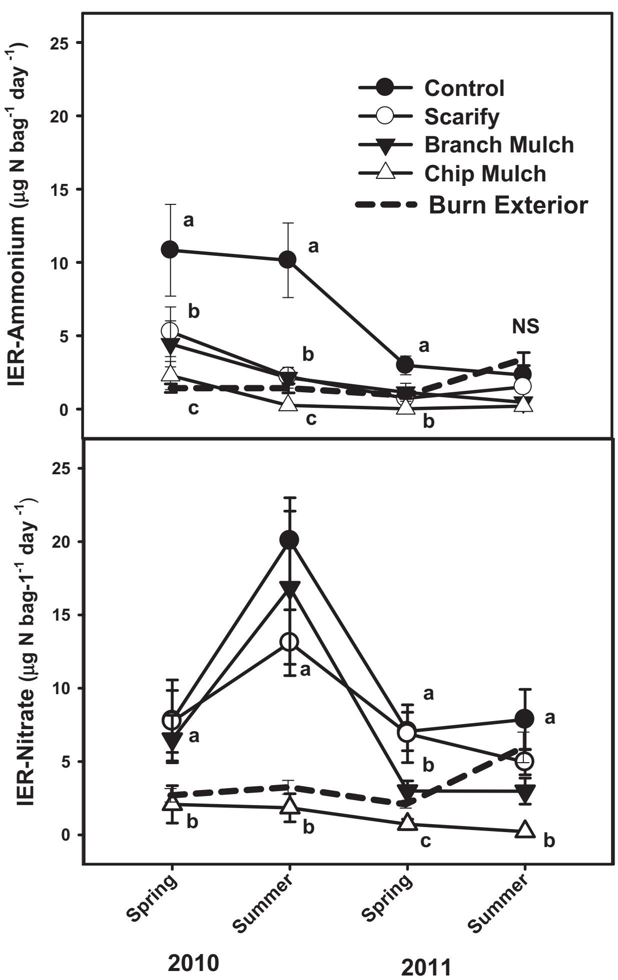

Fig. 3. Surface treatment effects on inorganic soil nitrogen measured with ion exchange resins (IER N) in the interior of pile burn scars at eight Front Range sites. Data are means and standard errors. Similar letters indicate that log transformed means did not differ significantly between treated and untreated pile interiors within seasonal sampling periods (Bonferroni adjusted $p < 0.05$). The dashed reference line shows mean IER N for unburned, exterior areas.

(Fig. 5). Forb species added in the seeding treatment became the dominant source of native forb cover, though seeding did not significantly increase overall forb cover relative to unseeded scars. Seeding had no effect on native graminoid cover. Addition of seed did not overcome the suppressive effect of woodchip mulch on native plant cover. With the exception of that treatment, native forb and graminoid cover were equal to that of unburned exterior areas. Native species richness responded both to surface treatments and seeding (Fig. 6). Two and a half years after pile burning, we found half the species richness in untreated scars compared to unburned areas. Addition of seed increased species richness of burn scars from 2 to 8.5 species on average.

Exotic plant cover was low in pile burn scars (1.8% in 2011) and largely unaffected by surface and seeding treatments. *Bromus tectorum* and *Cirsium arvense* were the most commonly encountered exotic species; both are classified as noxious in Colorado. Woodchip mulch suppressed exotic and native plants to a similar extent and seeding suppressed exotic plants marginally ($p < 0.1$).

4. Discussion

4.1. Pile burn effects and recovery

Small, hand-built piles, such as those we studied, are commonly burned in fuel reduction, hazard-tree removal and salvage areas in conifer forests of the Front Range and western North America. Our work documented that burning small piles had similar short-term effects on soil properties as larger piles (Tarrant, 1956; Ulery et al., 1993; Busse et al., 2013). However, in contrast to large piles, herbaceous plant cover and soil N availability recovered rapidly without rehabilitation treatments. Total native plant cover more than doubled over the course of our study in untreated pile scars, for example (Table 2). By the third growing season after burning, native forb and graminoid cover were comparable in untreated burn scars and unburned exterior areas (Fig. 5). These results agree with a study in Oregon lodgepole forests that found similar total plant cover in burn scars and adjacent areas within seven years of burning (Halpern et al., 2014). We also report that soil ammonium and nitrate peaked within 1.5 years of pile burning, and then returned to levels measured in unburned areas (Fig. 3). The lower mass of fuel

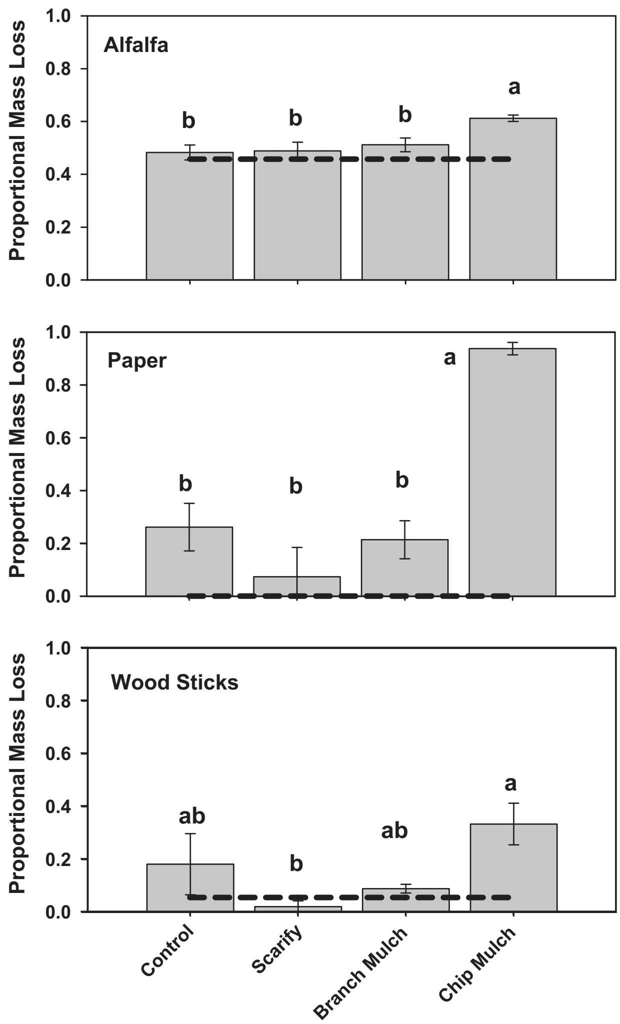

Fig. 4. Proportional mass loss of alfalfa litter, filter paper and wooden sticks in burn pile interiors during a one year period. Data are means and standard error for untreated and treated scars at eight conifer forest sites on the Colorado Front Range. Similar letters indicate that treatments means did not differ significantly within a substrate type (Bonferroni adjusted $p < 0.05$). Dotted reference lines show mean mass loss for unburned, exterior areas.

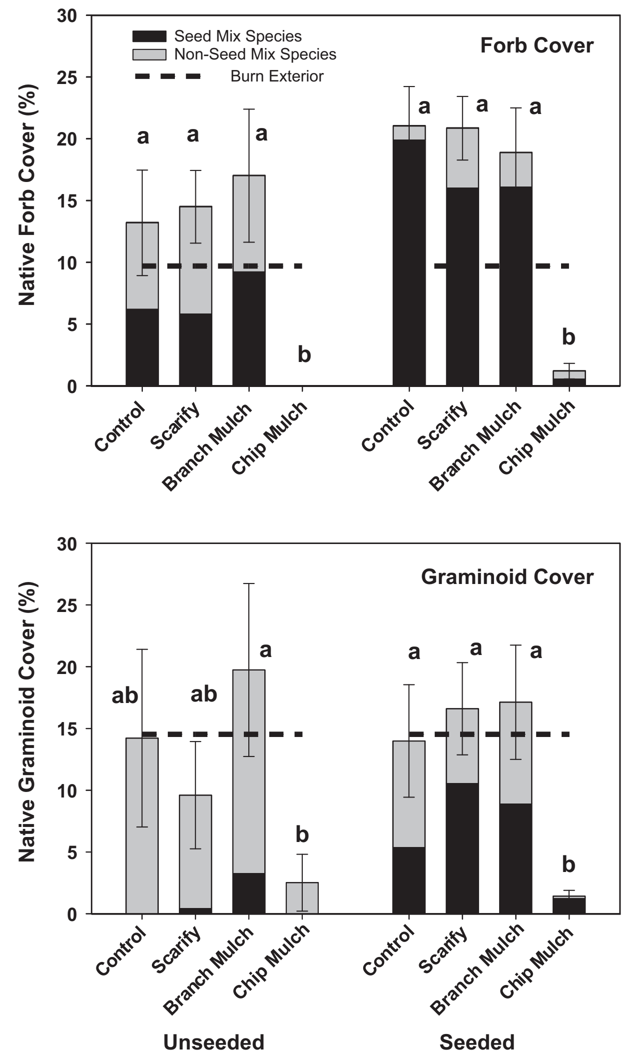

Fig. 5. Native forb and graminoid cover in 2011, two years after applying surface and seeding treatments to burn pile scars. Bars are mean cover with SE for 19 Colorado Front Range sites for Seed Mix Species (plants growing from sown seed plus volunteers) and Non-Seed Mix Species. Similar letters indicate that arcsine transformed means did not differ significantly between surface and seeding treatments (Bonferroni adjusted $p < 0.05$). Dotted reference lines show mean for unburned, exterior areas.

combusted reduces the severity and area disturbed by small burn piles and likely explains the rapid abatement of some of their effects.

Despite recovery of herbaceous plant cover and inorganic soil N, native plant diversity and shrub and organic soil cover remained significantly altered in small burn scars. Total native species richness was half that of unburned areas (Fig. 6), and shrubs comprised <1% compared to >10% cover in unburned areas. In Colorado lodgepole pine ecosystems, >10 m diameter burn scars remain identifiable, non-forested openings with low shrub cover for 50 years or more after burning (Rhoades and Fornwalt, 2015). Plant community composition will continue to change as longer-lived plant species become established and biogeochemical and physical processes alter burned soils. As noted for larger burn scars (Haskins and Gehring, 2004; Creech et al., 2012), we expect that compositional changes in the native plant community will remain evident for years after burning these small piles.

4.2. Rehabilitation effectiveness

Surface treatments had distinct effects on soil properties in pile burn scars. Application of woodchips significantly altered soil moisture, temperature, decomposition and soil N availability in small burn piles to a greater extent than other treatments. Similar to studies of mulching conducted for fuel reduction, we found that woodchip applications have the potential to decrease inorganic soil N (Reever-Morghan and Seastedt, 1999; Homyak et al., 2008; Rhoades et al., 2012). The consequences of mulch and other C sources on soil N availability are known to vary with mulch depth and time since treatment (Baer et al., 2003; Perry et al., 2010; Miller and Seastedt, 2009; Rhoades et al., 2012). Woodchip mulch rapidly dampened the increase in soil N availability after pile burning in these conifer sites. Similar to our current study, inorganic soil N declined significantly beneath deep, mulch beds (15 cm) in unburned conifer forests (Rhoades et al., 2012). Increased substrate decomposition (Fig. 4) is evidence that higher moisture (Fig. 1) and more stable temperatures (Fig. 2) in woodchip mulched soils are favoring microbial activity and likely contributing to N retention. Our current study indicates that applied shortly after pile burning, woodchip mulch has the potential to mitigate mineral and total N and sediment losses, as reported elsewhere (Schipper and Vojvodic-Vukovic, 2001; Foltz and Wagenbrenner, 2010; Johnson et al., 2011), and may be

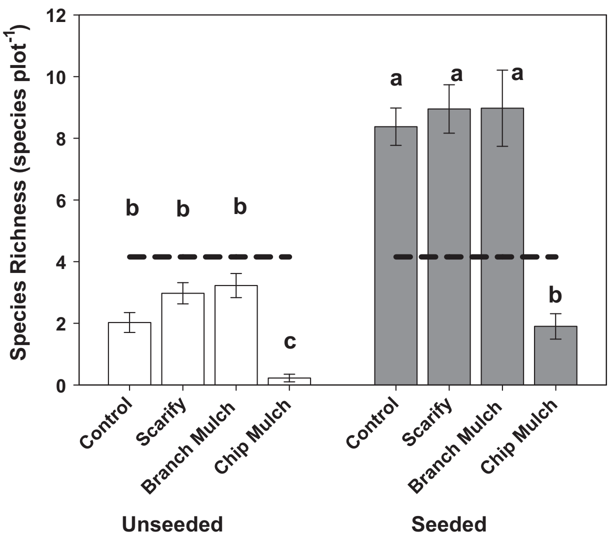

Fig. 6. Native plant species richness in 2011, two years after applying surface and seeding treatments to burn pile scars. Data are means and standard errors for 19 sites along the Colorado Front Range. Similar letters indicate that for arcsine transformed means did not differ significantly between surface and seeding treatments (Bonferroni adjusted $p < 0.05$). Dotted reference lines show mean for unburned, exterior areas.

appropriate for near-stream treatment areas where N released due to pile burning is most likely to impair water quality.

Woodchip mulch obstructed plant establishment on burn pile scars during the course of this study, even when combined with seeding. This differs from another Colorado Front Range study that found higher native grass cover in thinly mulched (~5 cm of woodchips) and seeded burn scars (Fornwalt and Rhoades, 2011). Operational scale, fuel reduction treatments that thin the forest canopy and create thin mulch layers (3–5 cm) also increased graminoid and forb cover in various Colorado forest types compared to untreated stands (Rhoades et al., 2012). The thicker mulch application of the current study (~10 cm) probably explains the low native plant cover. In light of expanding non-native plant populations in disturbed conifer forests (Sieg et al., 2003; Korb et al., 2004; Fornwalt et al., 2010), the suppressive effect of thick woodchip mulch may provide a quick and effective approach to reducing non-native plant establishment on soils exposed by pile burning, particularly in areas where non-native plants are abundant. The consequences of mulching on plant cover will diminish as wood chips decompose and longer-lived plants become established. Thick experimental mulch beds lose >50% mass, for example, 5–7 years after treatment in other Front Range conifer ecosystems (Rhoades et al., 2012; C. Rhoades, unpublished data).

Neither reduced seed availability (as evidenced by similar levels of native forb and graminoid cover in seeded and unseeded scars) nor altered soil properties hindered native plant establishment in small burn scars at these sites. As such, rehabilitation treatments may not be needed for all scars in these ecosystems. Larger pile burn scars, in contrast, are likely to require treatments to achieve desirable plant communities and adequate cover in an acceptable timeframe (Creech et al., 2012; Rhoades and Fornwalt, 2015), owing to more severe fire effects and soil compaction from logging equipment. For example, in contrast to plant recovery in these small burn scars, total plant cover was <10%, 2.5 years after burning in 10 m diameter piles at other Colorado conifer sites (C. Rhoades, unpublished data). Seeding the native grass *Bromus marginatus* increased plant cover to 45%, similar to total plant cover in surrounding unburned areas. Both the need rehabilitate pile burn scars and appropriate treatments vary with pile size, but must also consider site conditions and management objectives.

4.3. Management implications

Findings from this well-replicated study of pile burning support the following conclusions for management of small burn scars (<5 m average diameter) in Front Range ecosystems. Recovery of plant-available soil N and native herbaceous plant cover less than three years after pile burning suggests that rehabilitation of small pile burn scars may not be necessary except in sensitive areas with water quality and invasive plant concerns. Under such conditions, common to roadside and stream corridors, woodchip mulching is an appropriate way to dampen the post-fire pulse of plant-available soil N that can lead to nutrient inputs to surface water and promote weedy and non-native plants. Woodchip mulch had an equally suppressive effect on native and non-native plants, though non-natives were not abundant at our study areas. To maximize treatment benefits, mulching must be implemented within a year or two of pile burning.

These findings further suggest that creating small piles may be a management alternative with the potential to eliminate the need to rehabilitate large burn scars. However, large piles created on logging decks and during site preparation operations will remain a common forest practice so long as economically viable uses of small woody material are unavailable. The long-term trajectory of soil properties and plant communities in pile burn scars remain unknown, but these concerns are of secondary importance for land managers responsible for mitigating short-term losses of soil fertility, water quality impairment and exotic species invasion.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.03.026. These data include photographs of burn scars and rehabilitiaton treatments, plant species included in seed mix and Google maps of the most important areas described in this article.

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