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Short- and medium-term effects of fuel reduction mulch treatments on soil nitrogen availability in Colorado conifer forests

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ABSTRACT

Mechanical fuel reduction treatments have been implemented on millions of hectares of western North American forests. The redistribution of standing forest biomass to the soil surface by mulching treatments has no ecological analog, and this practice may alter soil processes and forest productivity. We evaluated the effects of mulch addition on soil nitrogen availability at 15 fuel reduction projects in the southern Rocky Mountains and Colorado Plateau regions of Colorado. Mulching treatments removed 38 Mg ha^{-1} of standing forest biomass on average and added 2–4 cm of irregular woody fragments to the O horizon. Mulching lowered maximum summer soil temperatures and increased soil moisture. The N added in mulch was equivalent to half the amount contained in untreated O horizons, and mulch had a lower N concentration and wider C:N ratio than material of similar size in untreated areas. Plant-available soil N, measured *in situ* with ion exchange resins was reduced under heavily-mulched experimental plots the year mulching occurred, but the effect did not persist for a second year. The nitrogen content of freshly-applied mulch increased by 9, 24 and 55 kg N ha^{-1} year^{-1} in plots receiving 22, 49 and 105 Mg ha^{-1} of mulch material on average. In contrast, 5-year-old mulch released N regardless of amount of mulch added. Three to five years after treatment, available N was 32% higher in mulched fuel reduction treatments compared to untreated forests. Heavy mulch application has the potential to temporarily reduce soil N availability in limited areas, but as implemented in Colorado conifer forests, fuel reduction mulch treatments increase soil N availability.

1. Introduction

Recent increases in the frequency of large, severe wildfires (Westerling et al., 2006) and extensive insect-related forest mortality throughout western North America (USDA, 2010) have prompted expansion of fuel treatment activities aimed at reducing potential wildfire size and severity (USDA/DOI, 2010). Wildfire historically regulated forest structure in most western conifer ecosystems, but opportunities to use prescribed fire to restore forest structure are limited by smoke restrictions and fear of fire escapes. Mechanical operations have become an increasingly common way to alter forest structure and fuel profiles (Kane et al., 2009; Reiner et al., 2009; Battaglia et al., 2010). From 2005 to 2011 mechanical fuel treatments were implemented on over 1 million hectares of forestland in the western US; mulching treatments represent approximately 10% of this area (NFPORS, 2011).

Commercial utilization of the small diameter trees, shrubs, and snags harvested during fuel reduction operations is limited, so the material is often chipped, shredded, or chunked and deposited on the forest floor. These treatments do not decrease the total fuel load at a stand level, but they reduce active crown fire risk by converting ladder and crown fuels into a surface layer of woody fuel (Agee and Skinner, 2005). Mechanical fuel reduction mulching treatments are being conducted in forest ecosystems across the western US, but little is known about the consequences of these treatments on soil and microclimatic factors that determine ecosystem productivity.

Woody mulch application has the potential to change soil nitrogen (N) availability. Similar to sawdust or sucrose additions, mulch may provide soil microbes a carbon (C) source that stimulates their growth and N demand and depresses inorganic soil N levels (McLendon and Redente, 1992; Gower et al., 1992; Blumenthal et al., 2003). In fact, labile C amendments are commonly used in ecosystem restoration to immobilize nitrogen and reduce the competitive advantage of high nutrient-demanding invasive plants (Zink and Allen, 1998; Baer et al., 2003; Perry et al., 2010). The addition of wood mulch has been shown to depress soil N availability both in eastern deciduous (Homyak et al., 2008) and western conifer forests (Miller and Seastedt, 2009). The depressive effects of C additions on soil N availability may be transient (Reever-Morghan and Seastedt, 1999; Perry et al., 2010), but owing

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to the slow decay of wood residue the added material is likely to create long-term physical changes to the O horizon.

The biogeochemical consequences of fuel treatments result from the net effect of vegetation removal and mulch deposition. In addition to the direct nutrient and C inputs in the mulch, understory and overstory removal can alter transpiration, interception, nutrient uptake, soil heating and soil moisture and thus influence microbially-mediated decomposition and nutrient cycling. A number of studies in western North American forests have found that woody residue deposited either as mulch or logging slash increases soil moisture and decreases soil temperature (Hungerford, 1980; Benson, 1982; Zabowski et al., 2000; Roberts et al., 2005; Busse et al., 2010). Mulch particles increase forest floor bulk density in general, though the mass of added mulch differs with the amount of basal area removed (Reiner et al., 2009; Battaglia et al., 2010; Kreye et al., 2011). The effects of mulching will likely differ among sites due to forest, soil and climatic conditions and management prescriptions that regulate the amount of canopy removal and depth of mulch deposited.

Continued use of forest mulching will require that land managers and the public have sufficient information about the ecological consequences of this relatively unproven treatment. The objective of this research was to determine if the effects of forest mulching on soil nitrogen nutrition that occur within 1–5 years of treatment can be generalized across Colorado's major conifer ecosystems. To help guide treatment implementation, we also evaluated the influence of residue application depth on mulching effects.

2. Methods

We evaluated the effects of mulch addition at 15 conifer forest sites distributed across the southern Rocky Mountains and Colorado Plateau regions of Colorado (Table 1), a subset of the 18 stands used for Battaglia et al. (2010). Study areas spanned climate gradients from relatively warm and dry pinyon-juniper (*Pinus edulis* Englem., *Juniperus* spp.) forests at low elevation to cool and moist lodgepole pine (*Pinus contorta* Douglas ex Loudon) and limber pine (*Pinus flexilis* James) dominated high elevation. In general, both precipitation and overstory basal area increased with elevation ($r^2 = 0.32$; $p = 0.008$); sites located above 2600 m (subalpine/mixed conifer forests) had 1.6-times more precipitation and basal area than the lower elevation sites (<2400 m) occupied by montane or pinyon-juniper forest (WRCC, 2011).

The subalpine/mixed conifer and montane sites were located along the Front Range from near the Colorado–Wyoming border to the Pikes Peak region. Pinyon-juniper sites were located in the Western Slope region and the San Juan Mountains in the southwestern corner of the State. Coarse-textured, slightly acidic to neutral soils (pH 5.1–7.1) soils derived from granitic, igneous and metamorphic materials were typical of the Front Range sites (Soil Survey Staff, 2011). Soils at most of upper elevation Front Range sites were classified as Dystocryepts. Soil properties varied widely among montane sites ranging from loamy Alfisols and Mollisols to sandy, skeletal Inceptisols and Entisols. Pinyon-juniper sites had generally finer-textured, more alkaline soils (pH 6.3–8.4), formed on sedimentary bedrock (sandstone or calcareous shale) or alluvial or eolian deposits.

Study areas were located on federal, state, and other agency lands, so treatment objectives varied among sites (Table 1). The most common management aim was to reduce the risk of crown fire initiation and spread. In some areas, treatments were conducted to remove beetle-killed or dwarf mistletoe-infected (*Arceuthobium vaginatum*) trees. Mulching occurred from 2001 to 2006 in all study areas, and research was conducted when treatments were 3–5 years old. Most areas were treated using a Hydroax™ masticator with a vertical shaft or rotary axe mower. Mastication equipment creates extremely irregular woody particles that are dominated by 1-h (<0.62 cm diameter) and 10-h (0.62–2.54 cm diameter) time-lag classes (Kane et al., 2009; Battaglia et al., 2010). In contrast, chipping creates smaller, more uniform fragments (Miller and Seastedt, 2009). Mechanical fuel reduction treatments removed 77% of the overstory basal area from upper elevation forests on average (Table 1). The lower elevation forests were less dense initially, and treatments removed less of the overstory (50%). However, mechanical treatments were effective at eliminating understory and ladder fuels (85% reduction) in these forests (Battaglia et al., 2010).

2.1. Operational and plot-scale measures

We combined operational-scale comparisons of mulched and untreated stands with plot-scale comparisons of mulch application depth. The operational-scale treatments did not include designated untreated, control areas, so we established post hoc controls in nearby forests outside the treated areas. We measured mulch, plant and soil attributes along three randomly-oriented, 50-m-long transects within mulched and untreated forest stands (see Battaglia et al., 2010 for details); sampling occurred 3–5 years after stand-level fuels treatments were conducted. Briefly, paired, mulched and untreated sites were situated within 1 km of each other with similar aspect, elevation and landscape position. We used pre-treatment stand inventories and post-treatment stump measurements to confirm that overstory structure and species composition were similar between mulched and untreated pairs. Co-located with our operational-scale study we created plots to compare shallow and deep mulch beds. Mulch collected in surrounding treatment areas was applied to adjacent 2×2 m plots to create 2.5 and 7.5 cm depth mulch beds for the pinyon-juniper sites equivalent to 23 and 70 Mg ha^{-1} of mulch, and 7.5 and 15 cm depths for the other forest types equivalent to 59 and 122 Mg ha^{-1}. Three replicates of the mulch bed treatments were created at each study area.

We characterized mulch, forest floor characteristics (Battaglia et al., 2010) and understory vegetation (Rocca, unpublished) in 1-m^2 quadrats distributed along each transect. Ocular cover estimates were made for herbaceous and woody plants, rock, exposed mineral soil, O horizon, and mulch material in 25 quadrats per transect. Mulch and O horizon depths were measured at the center and each corner of each quadrat. Surface fuel loads were estimated based on forest-type specific relations between mulch depth and cover (see Battaglia et al., 2010 for details). Added woody mulch and O horizon samples (fresh litter (Oi) and partially decomposed material (Oa and Oe)) were collected to determine dry mass and C and N content of various size materials. Mulch and O horizon samples were composited from three subsamples per transect and sorted into size classes (see Battaglia et al., 2010 for details). Size class samples were dried to a constant weight at 60 °C then ground prior to total C and N analysis by dry combustion (LECO Corp., St. Joseph, MI).

Plant-available soil N was assessed along the paired transects and in mulch bed depth plots using ion exchange resin (IER) bags (Binkley and Matson, 1983). Resin bags were installed at 5 m intervals along each transect (10 resin bags per transect), buried 5–10 cm deep in mineral soil. Four resin bags were installed in a similar manner in each mulch bed plot. The bags were constructed of permeable nylon fabric and filled with a mixture of cation and anion exchange resins (Ionac C 249 and ASB1P; Sybron Chemicals Inc., Birmingham, NJ) to retain nitrate (NO_3–N) and ammonium (NH_4–N) as these inorganic nitrogen forms percolate through the soil. Resin bags were deployed for 1 year along mulched and untreated transects and for two consecutive year-long periods in

Table 1
Site and treatment conditions at 15 fuel reduction projects in Colorado. Overstory structure data are mean values for trees >1 cm diameter sampled in three belt transects per study site. Total annual precipitation and annual temperature minima and maxima from nearby RAWS stations (WRCC, 2011).

Forest type	Elevation (m)	Precipitation (cm) Annual total	Temperature (°C)		Overstory basal area			Site name	Ownership
			Min	Max	Untreated (m^2 ha^{-1})	Mulched (m^2 ha^{-1})	Reduction (%)		
Subalpine/mixed conifer									
Pinus flexilis (44%), *Pinus ponderosa* (38%)	2900	9.3	−5.0	10.6	32.6	8.9	73	Catamount	Private
P. contorta (98%)	2818	10.3	−1.8	10.9	32.7	13.8	58	Golden Gate Canyon	CO State Park
P. contorta (100%)	2800	10.3	−1.8	10.9	31.3	15.7	50	Columbine	USFS
P. contorta (58%), *P. ponderosa* (30%) *Pseudotsuga menziesii (12%)*	2760	10.3	−1.8	10.9	34.8	3.4	90	Sugarloaf	USFS
P. contorta (100%)	2657	7.7	−8.1	11.3	38.3	12.4	68	Snow Mountain YMCA	Private
Montane									
P. ponderosa (94%), *Pseudotsuga menziesii* (6%)	2360	6.3	−1.9	17.1	16.7	7.4	56	White Spruce	USFS
P. ponderosa (58%), *Pseudotsuga menziesii* (42%)	2300	6.3	−1.9	17.1	28.6	13.7	52	Buck	USFS
P. ponderosa (68%), *Pseudotsuga menziesii* (32%)	2130	6.3	−1.9	17.1	26.2	6.7	74	North Fork	Private
P. ponderosa (50%), *Pseudotsuga menziesii* (50%)	2100	8.6	1.4	14.2	36.0	17.2	52	Lory State Park	CO State Park
Pinyon-Juniper									
P. edulis (89%), *Juniperus* sp. (10%)	2400	4.3	−1.7	17.2	30.2	5.5	82	Cherokee Heights	BLM
P. edulis (39%), *Juniperus* sp. (61%)	2250	7.3	−0.6	16.5	12.7	4.9	61	May Canyon	USFS
P. edulis (65%), *Juniperus* sp. (35%)	2200	3.8	1.4	17.4	17.2	6.4	63	Davewood	BLM
P. edulis (12%), *Juniperus* sp. (88%)	2200	4.7	−5.6	12.8	37.6	22.6	40	Pumphouse	BLM
P. edulis (22%), *Juniperus* sp. (78%)	2170	7.1	2.6	16.9	23.2	15.1	65	Summit	BLM
P. edulis (16%), *Juniperus* sp. (84%)	1915	5.1	0.5	18.1	11.5	2.5	78	Indian Camp	BLM

the deep and shallow mulch bed plots. After collection, bags were stored at 5 °C until the resins were extracted with 100 mL of 2 M KCl and analyzed for nitrate and ammonium by spectrophotometry (Latchat Company, Loveland, CO).

To compliment our assays of soil N availability, we characterized changes in the N content of standard mulch. We placed freshly produced (<1 year) and 5-year-old ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) residue within thick and thin mulch layers and on the surface of unmulched plots. A known amount of dried mulch material, equivalent to a 22 Mg ha^{-1} mulch layer was sealed within 30.5 × 30.5 cm plastic mesh bags that were attached to the soil surface. Mesh bags were removed after 24 months. Soil or roots adhering to the residue were brushed off and samples were dried and analyzed as described above for mulch and forest floor samples. Total N averaged 2.3 and 6.0 mg g^{-1} in fresh and 5-year-old mulch at the beginning of the study, respectively and the C:N ratio of fresh and aged mulch averaged 230 and 93 (*n* = 10 samples).

We measured the volumetric moisture content of the upper 10 cm mineral soil layer at 10 points distributed along mulched and untreated transects with a hand-held probe (CS 620; Campbell Scientific Inc., Logan, UT); sampling was conducted on one growing season date per site. Continuous measurements of soil temperature and volumetric moisture content were recorded at one pinyon-juniper and one lodgepole pine site (Onset Corp., Bourne, MA). Sensors were buried at 10 cm within the mineral soil beneath deep and shallow mulch layers and in adjacent, unmulched plots. Soil climate data was recorded on 10-min intervals.

We used mixed effects analysis of variance to evaluate differences between mulch treatments and forest types. Analyses were conducted using a mixed model with treatment and forest type as fixed effects and study site as a random effect (IBM SPSS Inc., Armonk, NY, V. 19). Soil and vegetation attributes sampled in 1 m^2 quadrats along the three belt transects were aggregated within the 15 site for the untreated and mulched treatments. Differences

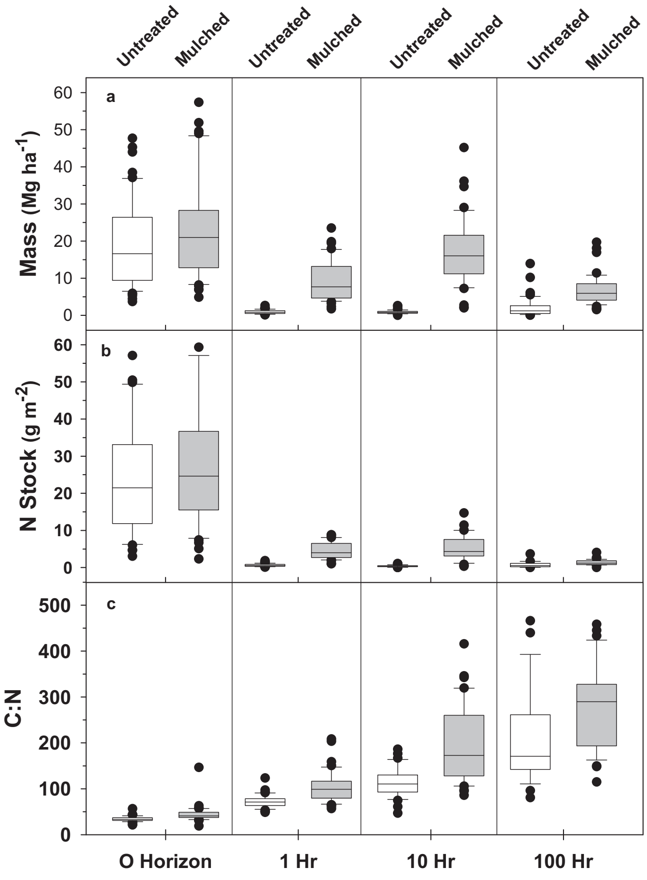

Fig. 1. Mass, nitrogen stock and C:N ratio of O horizon and woody fuel classes in mulched and untreated Colorado conifer ecosystems. Box plots show median, 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and outliers (filled circles) for samples collected 3–5 years after the treatments were established.

between shallow and deep mulch beds across forest type were analyzed using a mixed effects analysis of variance with mulch depth and forest type as fixed effects and study site as a random effect. We tested assumptions of normality and equal variance (Levene's test, Keyes and Levy, 1997) and log-transformed values as needed, to correct for unequal variances. Treatment effects were considered significant at $p < 0.05$, except where noted. Where significant depth effects occurred in the plot-scale experiment, Tukey's comparisons were used to identify differences among means. Graphical comparisons were made for soil temperature and volumetric moisture measured in mulch depth plots at one pinyon-juniper and one lodgepole pine site.

3. Results

3.1. Operational-scale effects

Mulching added residue as 1, 10 and 100 h fuel size class materials (29 Mg ha^{-1}) that were equivalent to 1.6-times the mass (Fig. 1) and twice the depth of the O horizon (Table 2) of untreated forests, on average. The cover of 1 and 10 h fuels (<2.5 cm size material) measured 3–5 years after the fuels treatments were conducted was 5 to 8-fold greater in mulched forests and that of 100 h fuels (2.5–7.5 cm size material) was 2 to 4-fold higher (Table 2) than in untreated forests. Mulch treatments had consistent effects on O horizon conditions and fuel and plant cover with few notable exceptions (Table 2). Overall, the cover of herbaceous plants (graminoids + forbs) doubled in mulched areas overall, and that of woody plants declined. Mulching increased the depth of the Oi (litter) layer in all forest types and decreased Oe + Oa (duff) depth in all but the pinyon-juniper forest type.

The 11 g N m^{-2} added in 1, 10 and 100 h size class material was half the amount contained in untreated O horizon (22 g m^{-2}, Fig. 1). Compared to O horizon layers or similar size material in untreated areas, mulch particles had lower N concentration and higher C:N ratio. One-hour size mulch particles for example, had half the N concentration of O horizon (5 vs. 12 mg N g^{-1}) and a C:N ratio that was more than 2.5-times wider. These general patterns were consistent across forest types, though the C:N ratio of both untreated O horizons and mulch residue were typically highest in the subalpine/mixed conifer group and lowest in the pinyon-juniper forests.

Plant-available N measured by ion exchange resins (total IER-N) averaged 1.0 mg N bag^{-1} in untreated forests and was predominantly in the nitrate form (82%; Table 3). The proportion of nitrate was highest in pinyon-juniper sites (93%) and lowest in the subalpine (68%). Overall, total IER-N was 32% higher in mulched treated areas ($p = 0.004$; Table 3). Both IER ammonium and nitrate were higher for mulched subalpine and montane forest sites compared to untreated sites; mulching increased total plant-available N about 50% in these forest types. Mulching did not have a consistent effect in pinyon-juniper sites. The treatment increased total IER-N 1.7- and 2.0-times, respectively in two of six pinyon-juniper forests, but had no positive or negative effect at the other sites.

Volumetric soil moisture was 1.3-times higher in mulched areas, overall ($p < 0.001$; Fig 2). Mulched subalpine and montane forests were 48% and 35% wetter, respectively, but mulching appears to have altered soil moisture at only two of five pinyon-juniper sites. The greatest mulch effects on soil moisture occurred at intermediate moisture contents (7–12%); mulching had little influences at high and low soil moisture.

3.2. Effects of mulch depth

The depth of applied mulch influenced both plant-available soil N and the mass loss and N content of mulch residue (Figs. 3 and 6). Overall, IER-N was 36% lower under deep mulch the year that the experimental beds were constructed ($p = 0.002$); both ammonium and nitrate forms of IER N were significantly less under thick

Table 2
Forest floor depth and ground cover measured in 1 m^2 quadrats at 15 fuel reduction project areas in Colorado. Data are means and standard error in parentheses. Significant mulch effects are identified within forest types using oneway analysis of variance as follows: *denotes $p < 0.05$; ** denotes $p < 0.01$.

Forest type	Depth (cm)		Cover (%)									
	Litter	Duff	Fuel classes			Forest floor	Rock	Soil	Graminoid	Forb	Shrub	Tree
			1 and 10 h	100 h	1000 h							
Subalpine/mixed conifer												
Untreated	1.9**	1.2**	3.9**	2.6**	1.1	81.7**	3.3	5.4	0.7**	0.5**	2.0	1.0*
	(0.1)	(0.1)	(0.3)	(0.4)	(0.4)	(1.7)	(0.7)	(1.2)	(0.1)	(0.1)	(0.5)	(0.2)
Mulched	3.6	0.4	37.7	7.2	0.7	46.3	2.3	4.1	2.1	1.6	1.4	0.5
	(0.2)	(0.1)	(2.4)	(0.5)	(0.2)	(2.5)	(0.5)	(1.0)	(0.5)	(0.2)	(0.3)	(0.2)
Montane												
Untreated	2.2**	1.4**	5.7**	2.0**	1.7*	77.8**	3.6*	7.5	1.4**	1.1**	5.0*	3.5
	(0.1)	(0.1)	(0.5)	(0.3)	(0.4)	(1.6)	(0.8)	(1.3)	(0.2)	(0.1)	(1.0)	(0.8)
Mulched	4.3	0.1	33.7	7.7	3.2	42.0	1.4	10.4	3.2	2.8	2.7	0.1
	(0.2)	(0.1)	(1.9)	(0.6)	(0.5)	(2.0)	(0.5)	(1.8)	(0.5)	(0.5)	(0.6)	(0.1)
Pinyon-juniper												
Untreated	1.1**	0.4	5.1**	0.9**	1.2	45.9**	11.2**	33.0**	2.2**	1.3*	7.3	5.9**
	(0.1)	(0.1)	(0.5)	(0.2)	(0.4)	(2.4)	(1.2)	(2.3)	(0.5)	(0.1)	(1.1)	(1.0)
Mulched	1.7	0.5	28.4	2.1	1.2	35.2	7.1	23.2	4.7	1.7	5.6	1.0
	(0.1)	(0.1)	(2.0)	(0.2)	(0.3)	(2.1)	(1.0)	(2.1)	(0.6)	(0.2)	(0.8)	(0.4)
Total												
Untreated	1.6**	1.0**	5.0**	1.7**	1.3	66.3**	6.5**	17.0	1.6**	1.0**	5.1*	3.8**
	(0.1)	(0.1)	(0.3)	(0.2)	(0.2)	(1.4)	(0.6)	(1.2)	(0.2)	(0.1)	(0.6)	(0.5)
Mulched	3.1	0.4	32.6	5.3	1.7	40.4	3.9	13.8	3.5	2.0	3.5	0.6
	(0.1)	(0.0)	(1.2)	(0.3)	(0.2)	(1.3)	(0.5)	(1.1)	(0.3)	(0.2)	(0.4)	(0.2)
Two-way ANOVA, main effects (p values)												
Treatment	<0.001	<0.001	<0.001	<0.001	0.214	<0.001	0.001	0.063	<0.001	<0.001	0.017	<0.001
Forest type	0.012	0.599	0.591	0.006	0.251	0.005	0.032	0.004	0.436	0.484	0.146	0.067
Treatment × forest type	<0.001	<0.001	0.002	<0.001	0.041	<0.001	0.204	0.001	0.486	0.010	0.601	0.002

Table 3
Soil N availability measured by ion exchange resins at 15 Colorado forest mulching sites. Data are means and standard error. Analysis of variance were conducted on log transformed data. Significant mulch effects are identified within forest types using oneway analysis of variance as follows: * denotes $p < 0.1$; ** denotes $p < 0.05$.

Forest type	IER-ammonium (mg N bag^{-1})		IER-nitrate (mg N bag^{-1})		Total IER N (mg N bag^{-1})		Nitrate proportion (%)	
	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched
Subalpine/mixed conifer	0.20 (0.02)	0.28* (0.04)	0.84 (0.09)	1.23* (0.18)	1.04 (0.11)	1.51** (0.19)	67.8 (2.45)	68.2 (2.35)
Montane	0.21 (0.04)	0.29* (0.04)	0.76 (0.07)	1.17** (0.14)	0.96 (0.10)	1.46** (0.15)	83.5 (1.43)	77.5 (1.78)
Pinyon-juniper	0.06 (0.01)	0.04 (0.01)	0.92 (0.09)	0.94 (0.09)	0.98 (0.10)	0.98 (0.09)	93.4 (1.01)	94.2 (1.00)
All types	0.16 (0.01)	0.20** (0.02)	0.84 (0.05)	1.11** (0.08)	1.00 (0.06)	1.32** (0.09)	81.6 (1.63)	80.0 (1.73)
Two-way ANOVA, main effects	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Treatment	4.61	0.032	6.66	0.010	8.26	0.004	1.54	0.215
Forest type	6.29	0.013	0.04	0.965	0.26	0.774	8.84	0.004
Treatment × forest type	3.56	0.029	1.40	0.247	2.12	0.121	2.90	0.056

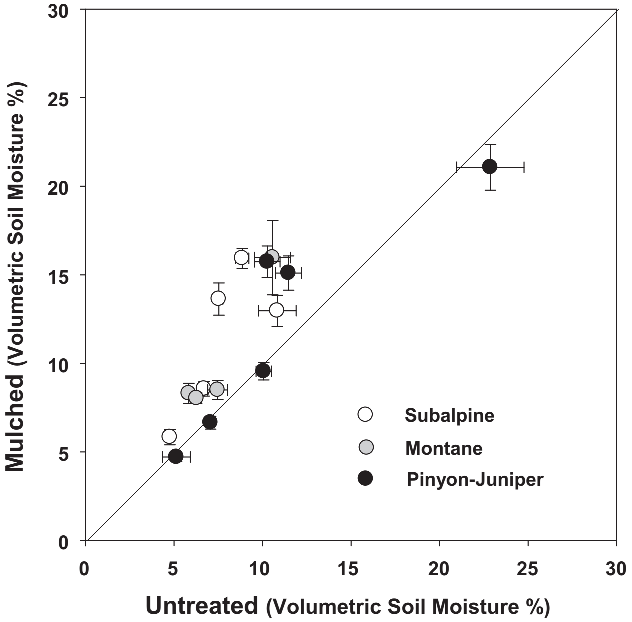

Fig. 2. Comparison of volumetric soil moisture (0–10 cm depth) measured in 15 mulched and untreated forest sites in Colorado on one growing season date per site. Dots are means and bars show standard errors of point measurements collected in each treatment type.

mulch beds. The second year after mulch bed construction, IER-N was similar for shallow and deep beds in all forest types.

The N content of standard mulch residue increased over the 24 month study period and its C:N ratio declined (Fig 6). Changes were more pronounced for material buried under thick mulch beds and for fresh rather than aged material. Averaged across depths the mass of fresh mulch declined 25%, 11% and 4% in montane, subalpine and pinyon-juniper sites, where older mulch lost 15%, 7% and 3%, respectively. Fresh surface-applied mulch lost 4% of its mass compared to 16% and 20% losses for material buried in thin and thick beds. The N concentration of fresh mulch increased from 2.3 to 3.8 mg g^{-1} on average. After correcting for mass loss over the 24 month period, fresh mulch added 17, 47 and 109 kg N ha^{-1} to surface applied mulch and mulch buried in thin and thick beds, respectively. In contrast, the N concentration and C:N ratio of old mulch changed little and it released N during the field study.

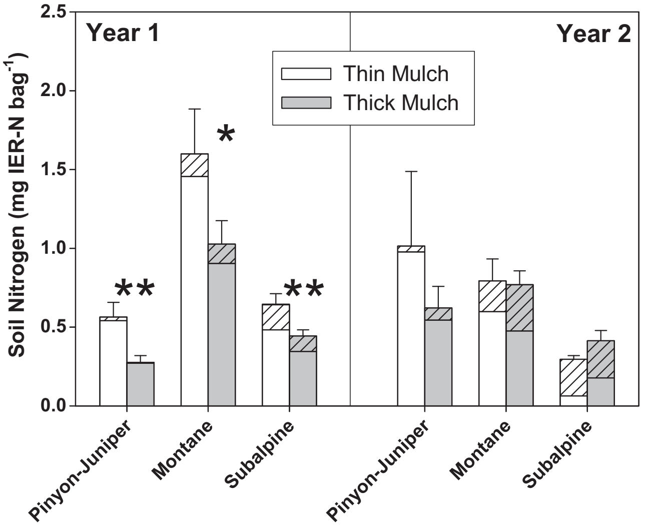

Fig. 3. Soil N measured by ion exchange resin bags under shallow and deep mulch beds at 10 mechanical fuel reduction project areas across Colorado. Stacked bars include IER-nitrate (hollow) and IER-ammonium (hatched). Means of total IER-N is shown with standard error bars. Asterisks denote significant mulch depth effect (*$p < 0.1$; **$p < 0.01$). Mulch bed depths differed among forest types; see Section 2 for details.

Mulch depth influenced soil temperature extremes (Fig 4) and averages (not shown). Maximum summer soil temperatures were 15 and 20 °C cooler beneath thin and thick mulch plots in the pinyon juniper site and about 4 °C cooler under mulch in the lodgepole site. Mean soil temperatures were 3.4 and 5.2 °C lower beneath thin and thick mulch compared to unmulched plots in the pinyon-juniper site and about 1 °C cooler in mulched lodgepole plots. Mulching appears to have been delayed spring soil warming by a few days under pinyon-juniper mulch beds, but had no effect in the lodgepole site.

The influence of mulch depth on volumetric soil moisture content differed both seasonally and between the two sites (Fig 5). At the lodgepole site, mulch effects were most evident during the drier months (summer, fall and winter) when soil moisture stayed at a relatively constant level in mulch beds. During that period, soil moisture was approximately equal to the level measured during spring snowmelt in the unmulched plots in both mulch bed depths. In the pinyon-juniper site, soil moisture responded to late summer precipitation in both mulched and unmulched plots. The two

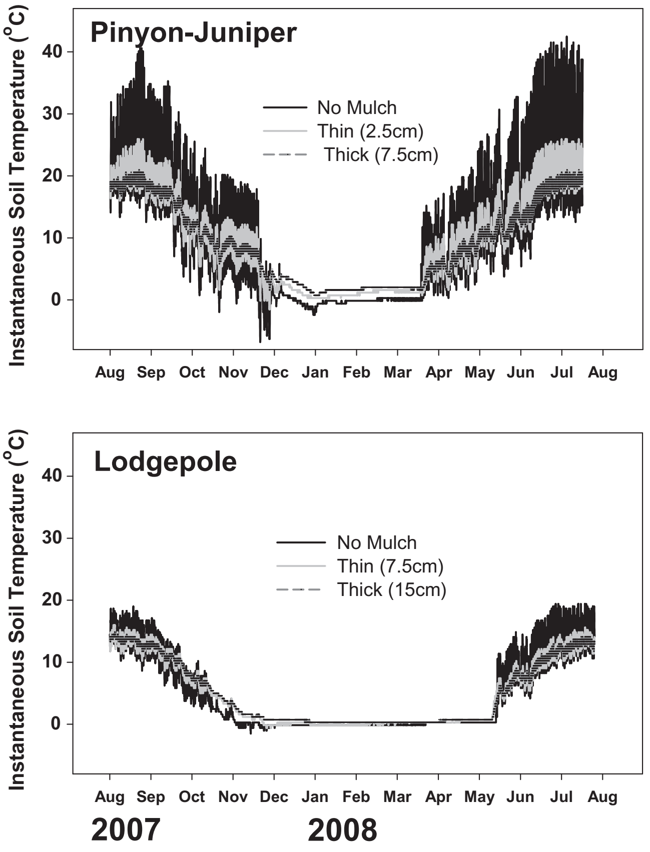

Fig. 4. Soil temperature (10 cm depth) in a pinyon-juniper and a subalpine, lodgepole pine forest in Colorado. Data are instantaneous values measured beneath thin and thick mulch beds and adjacent unmulched areas.

mulch depths influenced soil moisture fairly similarly in the lodgepole site, but in contrast, only the deeper mulch had a notable affect on soil moisture in the pinyon-juniper site.

4. Discussion

Operational-scale mulching increased soil N availability across a range of Colorado conifer forest types several years after treatment implementation (Table 3). In contrast, plot-scale studies often report that C or woody material additions immobilize N and reduce inorganic soil N pools for months to several years (Reever-Morghan and Seastedt, 1999; Baer et al., 2003; Perry et al., 2010). Several aspects of the forest fuel reduction mulch treatments we studied explain this apparent discrepancy. We sampled 3–5 years after the fuel reduction treatments were conducted. By that time the soil responses reported by short-term, plot-scale mulch application studies were likely to have subsided. Other studies have shown the time-dependant nature of soil responses to forest mulch application. For example, soil N availability was lower under woodchip plots the year after mulch was applied in a lodgepole pine forest (Binkley et al., 2003). A slight increase in soil N availability emerged 3 years after woodchips were added to a thinned, ponderosa pine forest (Miller and Seastedt, 2009). We measured lower soil N beneath thick mulch beds the year of treatment (Fig. 3), as well as an increase in the N contained within fresh mulch material (Fig. 6). Soil N availability the following year (Fig. 3) and the decline in N contained in old mulch (Fig. 6) suggest that any reduction in plant-available soil N may be relatively short-lived.

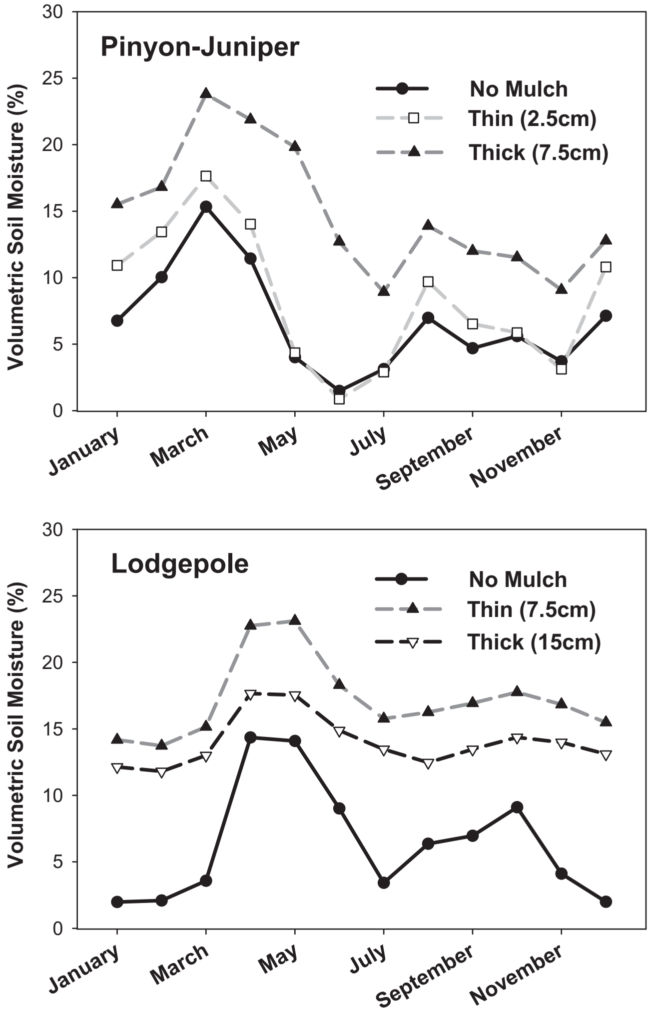

Fig. 5. Volumetric soil moisture (10 cm depth) in a pinyon-juniper and a subalpine, lodgepole pine forest in Colorado. Data are monthly mean values measured beneath thin and thick mulch beds and adjacent unmulched areas.

The effects of mulching on soil N availability appear also to be depth-dependent (Fig. 3). Similar to our depth manipulation, IER-N was lower under thick as opposed to thin woodchips (50% lower under 20 vs. 5 cm deep mulch) at a Colorado lodgepole site (Binkley et al., 2003). Higher C or woody residue application rates generally reduce soil N to a greater extent (Perry et al., 2010). Under the operational-scale conditions we studied however, there was no significant relation between IER-N and mulch depth or the cover of 1 and 10-h lag fuel classes. Fuel reduction operations removed 38 Mg ha^{-1} or 51% of standing tree biomass at our sites on average and created ~4 cm of mulch in subalpine and montane forests and 2 cm in pinyon-juniper (Battaglia et al., 2010). Less than 20% of the mulch measured along treated transects exceeded the depth of our thin experimental beds, and the thick experimental mulch beds were more than 3-times deeper on average than operationally-applied mulch. Total tree biomass was insufficient at most of our sites to create a stand-level mulch layer to the depth of our shallow experimental mulch bed (Hood and Wu, 2006; Battaglia et al., 2010). Irrespective of the stand treatment prescription, broad distribution of deep mulch would not be possible in these forest types.

4.1. Management implications

The ecological consequences of fuel reduction mulching treatments are the combined result of forest thinning and mulch

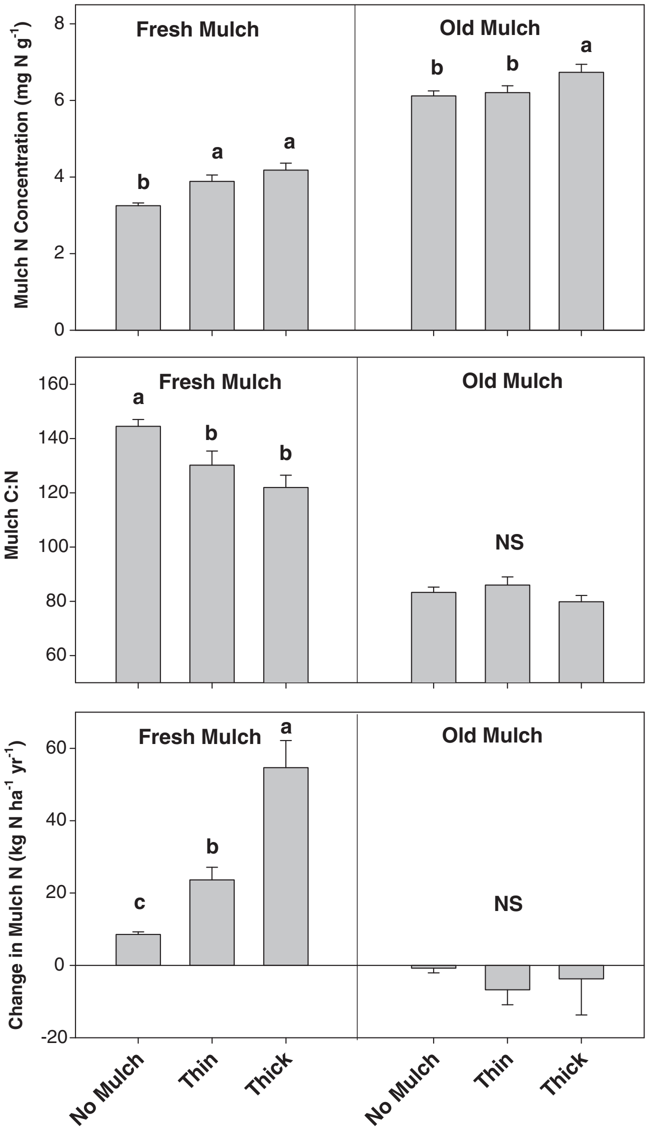

Fig. 6. Nitrogen concentration, C:N and N changes in fresh (1 year old) and old (5 year old) standard ponderosa pine mulch after 24 months in the field. Bars are mean values and standard errors. Similar letters and NS indicate that means did not differ at $p < 0.05$.

deposition. By reducing litterfall and tree nutrient and water demand and by altering the soil microclimate, forest harvesting often dramatically increases soil nutrient pools, leaching and nutrient losses in stream water (Hornbeck et al., 1986; Prescott, 2002; Aber et al., 2002). These changes often stimulate rapid regrowth and resource demand by herbaceous and woody vegetation that then modulate ecosystem responses to disturbance (Vitousek et al., 1979; Swank et al., 2001). In this study, higher soil N availability in mulched areas was the net outcome of decreased forest nutrient and water use balanced by increased N demand of understory plants plus N immobilization by microbes within added mulch (Downs et al., 1996). Evidence of N uptake within fresh mulch and lower soil N under deep mulch indicates that mulch applications have a substantial temporary effect on post-treatment soil N dynamics. Interactions among these processes differ across spatial scales and encompass the huge diversity of soil microbes, fluctuating environmental conditions, and impacts of removal of trees and their canopies (Kurka et al., 2001; Toljander et al., 2006; Lindahl et al., 2007). At a single site, the net treatment effects might be investigated by exploring the contributing and interacting factors, but across a broad geographic scale a first important step is to identify the overall pattern of response in soil N supply.

The woody residue generated by mulching treatments has a number of uses with potential for reducing soil and N losses and sustaining soil productivity and clean water (Robertson and Cherry, 1995; Homyak et al., 2008). For example, a variety of chipped and shredded wood-based materials have been found effective for post-wildfire erosion control (Foltz and Wagenbrenner, 2010). In a northern hardwood forest, 12 and 24 Mg ha^{-1} of woodchips immobilized 19 and 38 kg N ha^{-1} that may otherwise have been susceptible to post-logging leaching (Homyak et al., 2008); similar to our deeply-mulched plots, IER-N declined and chip C:N narrowed (from 125 to 70) the year after logging and wood chip application. Application of wood chips to soil damaged by piling and burning ladder fuels and logging refuse dampened the pulse of soil N common after combustion (Fornwalt and Rhoades, 2011).

As implemented in Colorado conifer forests, fuel reduction mulch treatments increased soil N availability within 3–5 years of treatment. Mulching increased total plant-available N by about 50% in subalpine and montane forest types but did not have a consistent effect in pinyon-juniper sites. We found lower soil N under experimental patches of thick mulch, but the amount of biomass treated in fuel reduction operations does not generate enough material to create deep mulch layers at a stand scale. Nevertheless, since forest growth is commonly limited by N supply, a reduction in soil N availability may impair tree growth if mulch is heavily concentrated and the long-term consequences of this relatively new practice on site productivity are unknown. Uncertainties regarding the potential for smoldering fires to cause severe soil effects during dry soil conditions and for more gradual changes in nutrient cycling as herbaceous and woody species respond to soil and microclimate changes following fuel reduction thinning operations and mulch application warrant further investigation.

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