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Microbial and nitrogen pool response to fuel treatments in Pinyon-Juniper woodlands of the southwestern USA

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ABSTRACT

Wildfire mitigation in Pinyon-Juniper woodlands in the Colorado Plateau region is a management priority. Two wildfire mitigation treatments, mastication and thin-pile-burn, are often chosen based on costs and availability of equipment, yet there are ecological concerns with either treatment. Ecological outcomes from additions of low quality organic residues following mastication can potentially alter microbially mediated soil nitrogen availability, therefore we wished to evaluate the effects of the additions of low quality woody residues to the soil surface compared to thin-pile-burn treatments at three *Ips confusus* affected woodland sites in the Colorado Plateau region. Thin-pile-burn treatments consisted of thinning between 40% and 60% of the canopy cover, while mastication treatments entailed shredding dead trees and 50% of shrub canopy while retaining live pinyon trees and designated snags. Both fuels treatments achieved wildfire mitigation goals, yet twice as much basal area and three times as much volume were removed by thinning relative to mastication. Surface additions of woody residues favored bacteria, while fungal populations that typically colonize and decompose woody organic residues did not increase in the upper mineral horizon. Neither fuel treatment affected mineral soils at the plot level, but the carbon to nitrogen (C:N) ratio of the organic horizon was significantly greater with mastication compared to the control. Nitrogen availability was reduced by almost half during the non-growing season, yet fuel treatments did not significantly influence nitrogen availability compared to control. Fuel treatment as performed in our study following the large mortality event demonstrated that microbial populations and their effects on nitrogen availability are resistant to disturbances produced by wildfire mitigations treatments.

1. Introduction

Fuel reduction strategies aim to reduce hazardous fuel loads and provide ecosystem services. Fuel treatments such as mastication, or mechanical thinning/piling followed with a prescribed burn potentially alter soil temperatures and available soil moisture by changing stand structure (Breshears et al., 1998; Zou et al., 2008) and surface conditions (Rhoades et al., 2012). Soil moisture, temperature, and mineralogy interact with plant detrital quality and quantity to control decomposition and mineralization (Meentemeyer, 1978; Paul and Clark, 1996; Poranzinska et al., 2003; Bardgett, 2005). Drought induced stress followed by pinyon bark beetle infestation (*Ips confuses* Leconte) culminated in over 1 million ha of pinyon (*Pinus edulis* Engelm.) mortality during the 2000–2004 period on the Colorado Plateau and southwest United States (Clifford et al., 2008; Allen et al., 2010). The extended drought and infestation by pinyon bark beetle prompted fuel treatments to limit the potential size and severity of wildfires (Battaglia et al., 2010; Hicke et al., 2012). These treatments also alter inputs to decomposition and N mineralization (Attiwill and Adams, 1993; Rhoades et al., 2012; Talbot and Treseder, 2012). In spite of frequent use, there are concerns about the effects of fuel treatments on the N dynamics, microbial populations, and potential for invasion of non-native species (Brockway et al., 2002; Owen et al., 2009).

Fuel treatments in pinyon-juniper woodlands are typically accomplished by hand-thinning, piling or broadcasting the slash, followed by burning to reduce fuel loads. This technique is labor intensive and can be relatively expensive. Prescribed burning of slash and surface litter in the piled areas decreases soil organic matter leaving a residue of ash or exposed bare mineral soil (DeBano et al., 1998). An alternative is to mechanically masticate or shred small standing live and dead trees and shrubs. Mastication modifies fire behavior by restructuring fuel profiles from ladder and crown fuels to surface fuels (Agee and Skinner, 2005; Battaglia et al., 2010; Kreye et al., 2014) and is economically less costly than thinning, piling, and burning. The deposition of high lignin content material, up to 45% for pinyon (Murphy et al., 1998), on the soil surface potentially increases N immobilization (Aber and Melillo, 1982;

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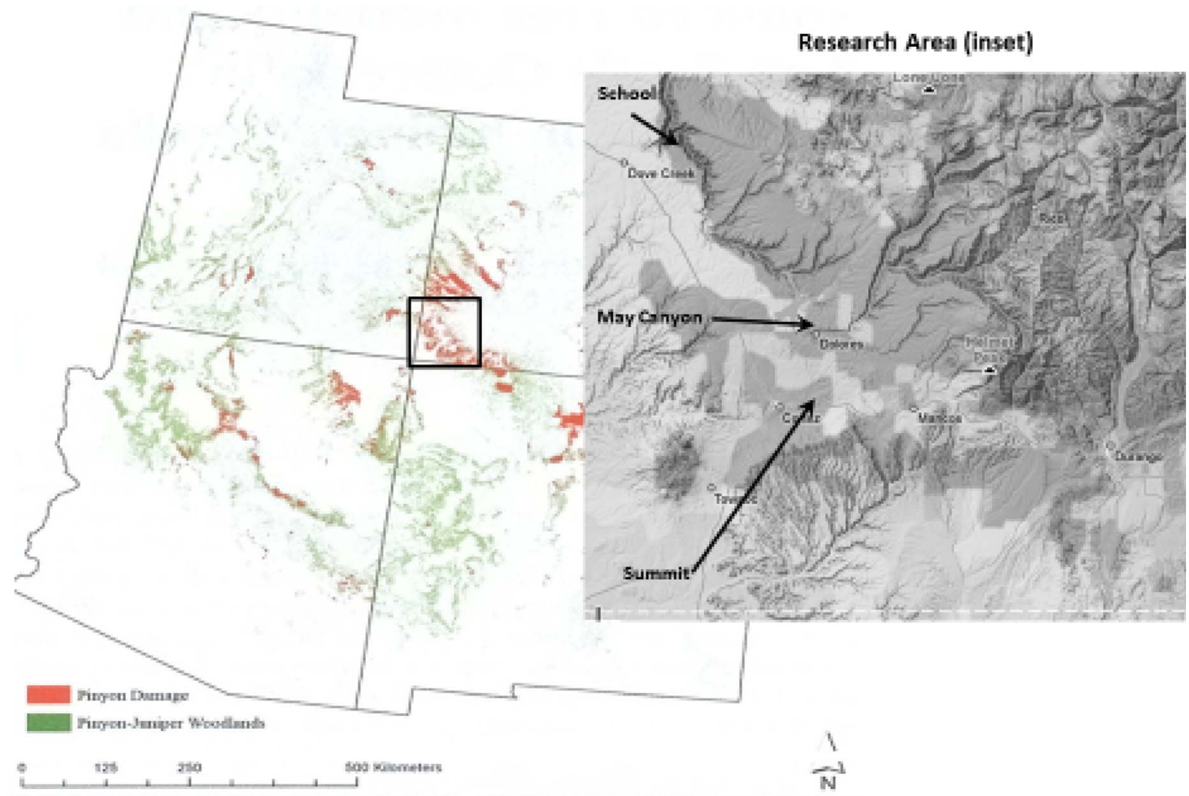

Fig. 1. Three fuels treatment study sites in the Colorado Plateau of southwest Colorado, USA.

Talbot and Treseder, 2012) and alters soil microbial populations (Blumenthal et al., 2003; Bardgett, 2005). Mechanical deposition of this high lignin and high C:N mass ratio organic residue on the soil surface is not comparable to any natural event (Rhoades et al., 2012).

Forest litter typically has a C:N ratio of 30:1 while pine wood has a ratio of 286:1 (Tisdale et al., 1985). Increasing C:N ratios of litter inputs should slow decomposition and turnover by microorganisms and immobilize N in the surface mineral soil (Wang and Bakken, 1997). Moisture deficits have also been shown to shift microbial communities to favor fungi (Harris, 1981) over bacteria (Nazih et al., 2001; Uhlirova et al., 2005), yet the addition of masticated woody debris increases available soil moisture and ameliorates soil temperature extremes (Brockway et al., 2002; Blumenthal et al., 2003). These abiotic changes should potentially lower fungi to bacteria (F:B) ratios, yet with the addition of woody material with a high C:N ratio, these changes favor increased F:B ratios (Bardgett et al., 1996; Myers et al., 2001; Siira-Pietikainen et al., 2001; Hogberg et al., 2007). Low quality litter with high C:N ratio and secondary compounds such as lignins and phenolics are linked with infertile soils dominated by fungi (Bardgett, 2005).

Thin-pile-burn can reduce total fuel loads, but there are ecological concerns due to the duration of heat pulse from pile burns (Owen et al., 2009). Fire can reduce detrital inputs to soil and result in the loss of decomposer microorganisms due to lethal temperatures (DeBano et al., 1998). Soil bacteria and fungi, the primary decomposers, process between 80% and 90% of all plant detritus via production of extracellular enzymes (Bardgett, 2005). Even though losses of organic matter due to combustion can be as high as 85%, increased nitrogen (N) availability (Covington and Sackett, 1992, Kaye and Hart, 1998, Hart et al., 2005), soil insolation and soil moisture (Hart et al., 2005, Simonin et al., 2007), surface soil pH (cation deposition), and the addition of charcoal (Hart et al., 2005) can enhance microbial activity (Pietikinen and Fritze, 1995; Pietikäinen et al., 2000). Yet prescribed fire can also

Table 1
Stand data for fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. Most of the trees removed during operations were classified as "dead" during the 2007 inventory.

		2005 (pre-treatment)			2007 (post-treatment)				
Site	Treatment	Pinyon live (trees per ha)	Pinyon dead	Juniper live	Pinyon live	Pinyon dead	Juniper live	Pinyon treated	Juniper treated
May Canyon	Control	165	114	163	172	121	174	0	0
	Mastication	310	106	29	304	141	18	101	4
	Thin-pile-burn	183	95	57	147	161	26	163	20
Summit	Control	249	348	233	310	374	240	0	0
	Mastication	306	312	229	275	312	147	216	53
	Thin-pile-burn	183	339	321	178	383	141	339	128
School	Control	218	11	79	275	26	90	0	0
	Mastication	244	55	46	180	139	37	125	20
	Thin-pile-burn	246	20	37	139	174	31	156	11

negatively impact soils by forming hydrophobic surface conditions limiting water infiltration and available soil moisture, reducing microbial activity (DeBano et al., 1998), and disproportionately decreasing fungal biomass especially in the surficial organic (O) horizon (Cairney and Bastias, 2007).

The goal of this research was to measure direct effects on soil microbial populations and soil N availability following mastication of dead trees and live shrubs and the more commonly utilized thin-pile-burn treatment. While mastication in woodlands in the Colorado plateau region of the southwest USA provides a cost effective alternative to thin-pile-burn fuels treatments, the ecological consequences of large artificially manipulated additions of low quality material to the soil surface to these woodland ecosystems is largely unknown. Our objectives were to (1) analyze microbial phospholipid fatty acids (PLFA) in the surface soils that provide quantitative measures of fungal and bacterial populations, and (2) measure *in situ* available inorganic N pool over time post-treatment utilizing Plant root Simulator (PRS™) probes[1] (WesternAg, Inc.) for both fuel treatments and an untreated control on large plots that more closely simulate management activities. A complicating factor in this research was the unknown impacts and lingering effects to the region due to the widespread mortality event prior to fuels treatments. Overall, the goal of these fuel treatments is to create a mosaic of open and wooded conditions that are capable of maintaining wildlife habitats, tree and shrub growth, increase herbaceous production, and reduce the risk of severe wildfire.

2. Material and methods

2.1. Study sites

Three sites were selected in southwest Colorado, U.S.A., designated as Summit, May Canyon, and School (Fig. 1). These sites are on public lands with two being on the San Juan National Forest and one on Bureau of Land Management (BLM). The sites are distributed over a 90 km distance. Summit and School sites are the farthest apart, while May Canyon is 15 km from Summit and 75 km from School. Most precipitation occurs during the rainy season of late July and August, while winter precipitation is often in the form of snow. Droughts are common. The research sites are all located on the Colorado Plateau and had been designated for fuel treatments prior to being selected as our study sites. Sites were dominated by pinyon and juniper (*Juniperus osteosperma* (Torr.) Little) trees with varying degrees of shrub understory (Tables 1 and 2).

The Summit study site (37°23′N108°24′W) is located on BLM land approximately 5 km north of Mesa Verde National Park. Soils are derived from residuum and alluvium from Mancos Shale (Ramsey, 2003). Surface soils are brown silty clay loam or light brownish gray clay loam of soil series Sidehow silty clay loam, Zigzag very channery clay loam, Zigzag-Sideshow complex, and Gladel-Pulpit complex. Weathered Mancos Shale occurs at depths of 48 cm. The elevation is 2134 m with mean maximum temperature is 18.2 °C, with mean minimum temperature of 0.6 °C, and mean annual precipitation 43.0 cm (all climate data from: http://www.wrcc.dri.edu/summary/climsmaz.html (Western Regional Climate Center, 2011)).

May Canyon study site (37°29′N108°30′W) is east of McPhee Reservoir and north of the town of Dolores on the San Juan National Forest at 2195 to 2256 m elevation. A typical soil is derived from colluvium and alluvium from sandstone and shale and soil surface texture is brown stony fine sandy loam (Ramsey, 2003) consisting of soil series Hesperus loam, Granath loam, Ilex-Granath complex, Wauquie-Dolcan complex, and Sheek-Archuleta-Rock outcrop complex. Mean maximum temperature is 16.5 °C, with mean minimum temperature −0.6 °C, and mean annual precipitation 47.8 cm.

The School site (37°55′N108°53′W) is ~8 km northwest of the town of Dove Creek. The soils are derived from either of eolian deposits or residuum from sandstone. The surface soils are classified as brown clay loams (Ramsey, 2003) from the soil series Nortez-Fivepine loams.

Table 2
Shrub cover data for fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. Values in parentheses are standard error of the mean.

		Control				Mastication				Thin-pile-burn			
		% cover											
Scientific name	Common name	2005	2006	2007	2008	2005	2006	2007	2008	2005	2006	2007	2008
Amelanchier utahensis	Utah serviceberry	11.18 (0.89)	9.83 (0.51)	8.39 (1.80)	7.05 (1.83)	12.73 (2.58)	7.21 (2.40)	7.09 (2.60)	6.76 (2.79)	6.70 (1.46)	4.67 (2.36)	3.31 (1.69)	4.97 (1.58)
Cercocarpus montanus	Alder-leaf mountain mahogany	11.39 (7.99)	6.57 (5.55)	9.30 (7.39)	8.88 (6.86)	9.32 (1.39)	4.49 (2.71)	7.57 (1.72)	5.26 (2.23)	6.86 (4.88)	4.51 (4.41)	2.96 (1.84)	3.33 (3.28)
Fendlera rupicola	Cliff fendlerbush	0.84 (0.43)	3.57 (3.57)	2.27 (2.27)	3.00 (2.95)	2.80 (1.46)	0.55 (0.55)	1.53 (1.53)	1.45 (1.45)	1.57 (1.57)	0.57 (0.57)	3.73 (3.73)	1.39 (1.39)
Peraphyllum ramosissimum	Wild crab apple	0.10 (0.10)	0.14 (0.14)	0.76 (0.76)	0.27 (0.27)	7.98 (4.97)	4.44 (2.66)	7.12 (4.33)	4.43 (2.44)	2.54 (1.79)	0.94 (0.74)	1.23 (1.18)	1.14 (1.09)
Pinus edulis	Pinyon	8.19 (1.09)	8.39 (1.77)	9.34 (0.85)	7.51 (1.37)	9.16 (1.93)	9.04 (3.33)	5.29 (1.28)	8.06 (1.07)	8.19 (1.09)	5.04 (1.69)	5.27 (2.67)	6.48 (3.21)
Purshia tridentata var. tridentata	Antelope bitterbrush	4.45 (2.23)	5.59 (1.99)	5.05 (0.94)	4.76 (2.69)	3.38 (2.21)	3.07 (1.63)	2.34 (1.24)	3.73 (2.14)	4.45 (2.23)	6.69 (1.24)	3.39 (0.23)	3.80 (1.16)
Quercus gambelii	Gambel oak	10.75 (4.32)	15.06 (5.64)	15.22 (5.54)	16.42 (4.81)	26.17 (2.56)	13.24 (0.96)	14.35 (1.86)	18.92 (1.20)	10.02 (5.05)	13.26 (6.75)	13.05 (6.64)	13.67 (10.18)
Juniperus osteosperma	Utah juniper	7.04 (0.66)	9.12 (0.20)	11.07 (2.83)	9.06 (1.10)	6.39 (4.31)	2.25 (1.13)	3.17 (0.21)	2.87 (0.27)	7.46 (0.31)	2.94 (1.44)	9.01 (3.88)	3.72 (1.89)
Artemisia nova	Black sagebrush	2.25 (1.53)	2.53 (1.83)	2.19 (1.90)	2.39 (2.39)	1.49 (1.49)	1.65 (0.84)	0.54 (0.54)	1.74 (0.98)	2.25 (1.53)	2.85 (1.63)	2.00 (1.42)	3.05 (1.48)
Symphoricarpos rotundifolius	Round leaf snowberry	0.38 (0.38)	0.43 (0.43)	0.82 (0.82)	0.60 (0.60)	2.11 (2.11)	1.47 (0.77)	2.86 (1.61)	2.74 (1.41)	0.38 (0.38)	0.43 (0.43)	3.50 (1.76)	3.10 (1.76)
Other		6.86 (3.53)	6.37 (3.02)	5.72 (3.64)	5.93 (2.96)	11.18 (3.40)	4.22 (1.51)	3.12 (1.90)	4.17 (1.96)	13.22 (5.44)	11.94 (9.93)	3.92 (0.98)	7.15 (5.30)

Table 3
Average litter/duff and woody fuel depths (cm) by treatment in 2005 (pretreatment) and 2007 (post-treatment) for fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006.

Site	Treatment	Litter/Duff 2005	Litter/Duff 2007	Woody Fuels 2005	Woody Fuels 2007
School	Control	0.51	1.27	1.02	1.52
	Mastication	1.02	2.03	4.32	3.81
	Thin-pile-burn	0.76	2.29	2.29	5.08
Summit	Control	0.76	1.02	9.14	11.94
	Mastication	1.78	2.79	7.37	5.33
	Thin-pile-burn	1.27	1.52	3.56	3.56
May Canyon	Control	1.78	1.78	11.43	11.43
	Mastication	2.79	4.32	3.81	4.57
	Thin-pile-burn	0.51	2.29	2.54	8.13

Elevations range from approximately 2256 to 2378 m. Mean maximum temperature is 16.0 °C, with mean minimum temperature 2.28 °C, and mean annual precipitation 40.4 cm.

2.2. Experimental design

The experimental design was a randomized complete block with three blocks and three treatments: mastication, thin-pile-burn, and an untreated control. Three 14.2 ha plots were established on each of the three sites. The three treatments were assigned randomly to the three plots on each site. Steel posts marked the corners of each plot. Six transects were located along a baseline at the plot's northern edge and ran due south through the plot. Start locations along the baseline were randomly selected but with the restriction that three plots must be on each half of the baseline and starts cannot be closer than 30.5 m from each other. Six sampling points were located randomly on each transect with the restriction that no two points can be closer than 30.5 m from each other. There were 36 points on each treatment plot. Steel pins were installed and flagged during the pretreatment phase to assist in locating points, but were removed prior to treatments, then relocated following treatments. The intent was to measure the same points over time. The Dolores Public Lands Office (shared management of BLM and US Forest Service lands) designed and supervised the mastication and thinning treatments.

Mastication began in the fall of 2005 and was completed in the winter 2006 at a time of low beetle activity. A large hydraulic mower mounted on a rubber-tired front-end loader was utilized for the mastication treatment. Management's contract mastication guidelines called for the creation of a random mosaic of small openings and reduced tree densities (2.5–25 cm diameter at breast height). Eighty percent of the treated woody material was less than 2.54 cm in diameter, and less than 15.24 cm long, and was deposited on the soil surface. Live pinyon trees and designated snags were to be protected and 50% of the shrub canopy was to be retained. Small areas were left untreated to avoid steep slopes (> 25%), arroyos, sensitive soils, archeological resources, or to meet other resource management concerns. Thin-pile-burn treatments consisted of thinning between 40% and 60% of the canopy cover, targeting pockets of live pinyon and juniper trees and dead pinyon, retaining some saplings, groups of closely spaced trees, and trees larger than 20 cm diameter at breast height, and thinning 50% of the shrub canopy (Tables 1 and 2). The piles of wood were then burned in early 2006.

2.3. Tree and shrub measurements

The overstory was measured to determine pre- and post-treatment conditions using 0.02 ha fixed plots (36 plots per treatment). Overstory measurements included species, diameter at root collar, total height, crown diameter, insect or disease conditions, and plant condition (including mortality). Dead and down material was measured using a modified Brown Technique (Brown, 1974). Shrub composition and canopy cover was measured using the line intercept method adjacent every fourth overstory plot (9 line intercepts per treatment). The start and end points (to the nearest 0.03 m) of the vertical projection of foliar cover by species was recorded. Small gaps within one shrub of up to 0.15 m were ignored but gaps that were wider than 0.15 m were recorded as having no cover. Shrubs were recorded by three classes; (1) dead (the entire shrub is dead), (2) live (any part of the shrub is live), and (3) dead within live (there is a major dead branch or section within a live shrub). If trees species were shorter than 1.4 m, they were included in the line intercept method.

Mastication inputs increased the litter/duff depths by 50% at the School site, while both Summit and May Canyon site increased ~35% (Table 3). Woody fuel loading fluctuated between pre-treatment and 2007 post-treatment sampling (Table 3). Initial values were very large at Summit which had the highest stand density, greatest amount of *Ips confusus* mortality and a relatively large number of old and declining juniper trees. The controls and thinning plots on all three sites indicate an increase between 2005 and 2007.

2.4. O-horizon and mineral soil sampling and analysis

O-horizon and mineral soil samples were taken within the same two week period of each year from 2005 to 2008 at randomly located points within 1 m of the location pin. The O-horizon was collected within a 0.01 m^2 frame and an associated soil sample was obtained directly

Table 4
Mass measurements for the organic horizon in southwest Colorado, USA fuel reduction study. Mastication and thin-pile-burn treatments done winter of 2005–2006. Different letters for a given sampling date indicate significant differences, but sampling dates that share letters are not significantly different (α = 0.05) using Tukey-Kramer pairwise comparison following a significant repeated measures, generalized linear mixed model analysis of treatments. When no letters are provided, mean values among treatments were similar statistically. Values in parentheses are standard error of the mean.

Treatment	Year	n	O-horizon mass (std. error of mean) $Mg{\cdot}ha^{-1}$	Total Carbon (std. error of mean)	Total Nitrogen (std. error of mean)	C:N mass ratio
Control	2005	3	54.11 (6.36)	12.12 (1.53)	0.52 (0.02)	23.08 (2.14)
Masticated	2005	3	33.13 (8.01)	7.87 (1.67)	0.36 (0.09)	21.99 (2.05)
Thin-pile-burn	2005	3	39.27 (4.42)	8.99 (1.36)	0.42 (0.18)	21.81 (0.93)
Control	2006	3	38.53 (14.55)	9.74 (3.78)	0.38 (0.12)	24.19 (1.98)a
Masticated	2006	3	39.39 (8.51)	11.93 (3.00)	0.43 (0.09)	27.45 (1.05)b
Thin-pile-burn	2006	3	28.58 (2.95)	7.43 (1.05)	0.31 (0.06)	24.58 (1.42)a
Control	2007	3	40.69 (9.53)	8.11 (1.64)	0.31 (0.06)	25.89 (1.36)a
Masticated	2007	3	35.08 (7.04)	9.95 (1.87)	0.33 (0.05)	30.84 (3.31) b
Thin-pile-burn	2007	3	37.74 (8.53)	8.12 (0.69)	0.32 (0.03)	25.19 (1.15)a
Control	2008	3	36.19 (1.03)	7.28 (0.08)	0.30 (0.03)	24.08 (1.75)a
Masticated	2008	3	37.20 (6.75)	11.19 (2.08)	0.38 (0.11)	32.10 (3.77)b
Thin-pile-burn	2008	3	36.19 (4.63)	9.96 (1.68)	0.37 (0.08)	27.10 (1.09)a

Table 5
Total carbon, nitrogen, mass ratio, and pH for mineral soil during fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. There were no significant differences (α = 0.05) using Tukey-Kramer pairwise comparison following a significant repeated measures, generalized linear mixed model analysis of treatments. Values in parentheses are standard error of the mean.

			Total Carbon (Mg·ha^{-1}) (std. error of mean) Soil depth		Total Nitrogen (kg·ha^{-1}) (std. error of mean)		C:N ratio (std. error of mean)		pH (std. error of mean)	
Treatment	Year	n	0–5 cm	5–15 cm	0–5 cm	5–15 cm	0–5 cm	5–15 cm	0–5 cm	5–15 cm
Control	2005	3	41.14 (11.12)	42.37 (7.94)	2.03 (0.20)	2.75 (0.04)	15.54 (1.03)	15.42 (2.98)	6.87 (0.03)	6.86 (0.04)
Masticated	2005	3	40.19 (12.17)	32.91 (12.78)	2.22 (0.23)	2.03 (0.29)	17.41 (3.55)	15.19 (3.64)	6.82 (0.05)	7.05 (0.05)
Thin-pile-burn	2005	3	31.14 (1.12)	51.46 (17.42)	2.61 (0.33)	3.30 (0.62)	15.70 (2.99)	17.43 (5.14)	6.89 (0.05)	7.11 (0.04)
Control	2006	3	36.31 (1.50)	42.78 (6.83)	2.51 (0.25)	2.30 (0.26)	14.63 (0.83)	10.79 (4.10)	6.90 (0.06)	6.81 (0.07)
Masticated	2006	3	43.47 (14.77)	24.91 (6.15)	2.45 (0.31)	1.99 (0.03)	16.84 (3.50)	12.46 (2.91)	6.87 (0.04)	7.01 (0.05)
Thin-pile-burn	2006	3	43.87 (14.11)	48.31 (15.53)	2.31 (0.30)	2.35 (0.44)	18.06 (3.54)	20.63 (4.52)	6.85 (0.05)	7.09 (0.06)
Control	2007	3	33.41 (4.06)	47.73 (6.10)	2.14 (0.06)	2.49 (0.49)	15.55 (1.62)	16.88 (3.54)	6.84 (0.06)	6.85 (0.08)
Masticated	2007	3	38.42 (13.29)	17.54 (4.38)	2.05 (0.28)	1.33 (0.06)	18.03 (4.49)	13.29 (3.48)	6.90 (0.06)	7.02 (0.08)
Thin-pile-burn	2007	3	44.83 (11.78)	44.71 (15.93)	2.43 (0.33)	2.08 (0.43)	18.11 (3.68)	21.21 (5.50)	6.92 (0.06)	7.07 (0.07)
Control	2008	3	28.73 (3.74)	44.29 (10.80)	1.83 (0.19)	1.90 (0.02)	15.70 (1.21)	18.96 (3.43)	6.85 (0.06)	6.86 (0.08)
Masticated	2008	3	31.76 (11.47)	20.64 (3.76)	1.78 (0.25)	1.66 (0.37)	16.91 (3.69)	12.83 (1.93)	6.97 (0.06)	7.04 (0.07)
Thin-pile-burn	2008	3	42.45 (13.41)	46.16 (14.99)	2.24 (0.27)	1.88 (0.11)	18.51 (3.58)	24.43 (7.66)	6.98 (0.06)	7.01 (0.08)

under the O-horizon sample. The O-horizon post-treatment includes pre-treatment plus additions resulting from mastication. Mineral soil samples were taken using a slide hammer with a 5 cm × 15 cm corer attached (AMS, Inc. American Falls, ID 83211). The O-horizon and mineral soil samples were placed into polyethylene bags, then inside cold storage containers for transport back to the laboratory. Upon return to the laboratory gravimetric moisture content was determined for each sample to provide dry weights used in calculation of chemical analysis.

The O-horizon and mineral soil (0–5 cm, 5–15 cm depths) analyses of uniformly mixed subsamples were analyzed for% total C and N by thermal conductivity detection after combustion at temperatures up to 1200 °C on a commercially available elemental analyzer (ThermoQuest EA Flash 1112, Milan, Italy). Soil pH was determined by immersing a glass electrode into a 1:5 (w/v) soil-to-0.01 M $CaCl_2$ solution (Hendershot et al., 1993) connected to a Orion 550 A pH meter (Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA).

In situ ion flux of bioavailable N as a function of N mineralization and/or dissolution over two seasonal sampling periods were assessed using the PRS™-probes. These probes consist of membranes (17.5 cm^2) containing ion exchange resins (IER) that measure dynamic ion flux (Binkley and Matson, 1983). When chemically pre-treated, the anion and cation exchange resin membranes exhibit surface characteristics and nutrient sorption phenomena that closely resemble a plant root surface. When buried in soil, the PRS™-probe can assess nutrient supply rates by continuously adsorbing charged ionic species over the burial period (Qian and Schoenau, 2002). These probes were placed inside of 10 cm dia. × 15 cm depth PVC tubes to eliminate roots. The probes were placed within the top 5 to 7 cm of mineral soil with original litter layer placed back on top of the mineral soil. After a six month incubation, the PRS™ probes were collected and returned to the laboratory where they were rinsed with DI water to remove all soil particles, placed in Ziploc® plastic bags prior to shipping to Western Ag Innovations of Saskatchewan, Canada. Western Ag Innovations Inc. eluted the PRS probes in the Ziploc® plastic bags with 0.5 M HCl solution, then analyzed colorimetrically using a segmented flow autoanalyzer. Blanks probes were included to determine any potential background N on the membranes. The PRS™-probes provide a dynamic measure of ion flux to a sink with a known surface area that we call available inorganic N pool for this study. Our placement and re-insertion in the same location captured the net pool of decomposable N post-treatment in the absence of plant roots and for some locations the absence of fresh litter inputs. Some of the random sample locations were not directly influenced by treatments, therefore they still received fresh litter inputs.

Mineral soil phospholipid fatty acids (PLFA) were used to assess microbial biomass and structure. Mass spectral analysis identified numerous compounds between C14 to C22 in C chain length, of which 16 were used as microbial biomarkers. Individual PLFAs can be used as specific biomarkers to identify either bacteria or fungi and as an index for total microbial biomass (Frostegard, 2011). Five g of freeze-dried mineral soil or 2 g of freeze-dried ground litter was extracted with a single-phase mixture of chloroform, methanol, and phosphate buffer (White et al., 1979) then fractionated into neutral, glyco-, and phospholipids (Frostegard et al., 1991). We followed the extraction and analysis method described in Schweitzer et al. (2008). Quantification (nmol PLFA kg^{-1} oven-dry material) of samples was based on calibration curves derived from individual fatty-acid methyl ester standards.

2.5. Statistical methods

We used a repeated measures generalized linear mixed model to

Table 6
Net nitrogen captured by Plant Root Simulators (PRS™-probes). Mastication and thin-pile-burn treatments done winter of 2005–2006. Different letters for a given sampling date indicate significant differences (α = 0.05) using Tukey-Kramer pairwise comparison following a significant repeated measures, generalized linear mixed model analysis of treatments. When no letters are provided, mean values among treatments were similar statistically. Values in parentheses are standard error of the mean.

Treatment	Time period	Total PRS probe N (mg N · 17.5 cm^2)	PRS probe NO_3-N	PRS probe NH_4-N
Control		290.9 (40.4)	284.5 (39.8)	6.5 (1.2)
Masticated	July 2006 -Nov. 2006a	225.0 (31.8)	220.4 (31.8)	4.6 (0.5)
Thin-pile-burn		285.8 (36.0)	279.8 (35.4)	6.0 (1.5)
Control		146.9 (37.4)	139.7 (36.6)	7.2 (3.7)
Masticated	Nov.2006-July 2007b	73.1 (12.9)	69.2 (12.8)	3.9 (0.8)
Thin-pile-burn		133.6 (25.8)	127.9 (26.2)	5.7 (1.9)
Control		272.1 (43.5)	268.6 (43.5)	3.5 (0.4)
Masticated	July 2007 -Nov. 2007a	338.5 (91.6)	326.0 (92.3)	12.5 (4.2)
Thin-pile-burn		208.0 (26.3)	204.8 (26.3)	3.2 (0.5)
Control		213.4 (43.7)	209.8 (43.3)	3.6 (1.2)
Masticated	Nov.2007-July 2008b	121.4 (23.2)	118.6 (23.0)	2.8 (0.9)
Thin-pile-burn		151.5 (18.8)	148.8 (18.6)	2.7 (0.8)
Control		110.9 (30.0)	104.3 (29.0)	6.6 (1.8)
Masticated	July 2008 -Nov. 2008c	89.6 (15.9)	85.3 (15.8)	4.4 (0.9)
Thin-pile-burn		157.0 (42.0)	151.9 (41.9)	5.1 (0.7)

statistically analyze total C and N contents, pH, soil moisture and inorganic N pool size (GLIMIXX, SAS for PCs ver. 9.3, Copyright © 2011, SAS Institute Inc., Cary, NC, USA) to determine differences based on treatment, sampling date, and treatment × sampling date interactions. We designated site as a random effect while using sampling date (categorical time interval) as our repeated measure. The designation of site as a random effect allows a greater scope of inference across these heterogeneous sites as the variation due to site can be quantified (Bolker et al., 2008). A log link function was utilized for analysis of O-horizon mass, total C and N, C:N mass ratios, and available inorganic N pool due to exponential distribution of the data. For available inorganic N pool we performed natural log transformation due to heteroscedasticity. This procedure tests for differences in treatments on response variables adjusted for any pre-treatment site spatial dependence to the response variable. The temporal correlation is nested within each site and treatment combination. Each subject is a site × thin × burn combination such that the temporal correlation within each site is modeled and not pooled across sites. An unstructured variance–covariance matrix is fit to account for inter-year correlation in each treatment × block combination. The variances are constrained to be non-negative, while the covariance matrix of the fixed-effect parameter estimates (treatments) are unconstrained in order to avoid non-linear constraints. Denominator degrees of freedom for t and F tests were determined using Kenward-Roger approximation (Bolker et al., 2008). Tukey-Kramer grouping was utilized for testing significant differences among least square means.

Microbial community structure (PLFA) was analyzed using multi-response permutation procedure (MRPP; Mielke and Berry, 2001). Multi-response permutation procedure is a non-parametric technique; therefore does not require assumptions of multivariate normality or homogeneity of variances, which are seldom met with ecological community data (McCune and Grace, 2002). Simultaneous pairwise comparisons of treatments tested the null hypothesis that all treatment pairs are similar. Fungal to bacterial ratios (F:B) were also statistically analyzed using GLIMIXX/SAS software procedure as described above. A correlation matrix of measured variables in the upper soil horizon was produced using SAS software. Correlations are based on Pearson's product-moment correlations with an alpha value of 0.05.

3. Results

Mastication of standing dead and live fuels did not significantly add to the total mass of the O-horizon or total C and N individually at the plot scale (Table 4); yet total C:N ratios increased for three years post-

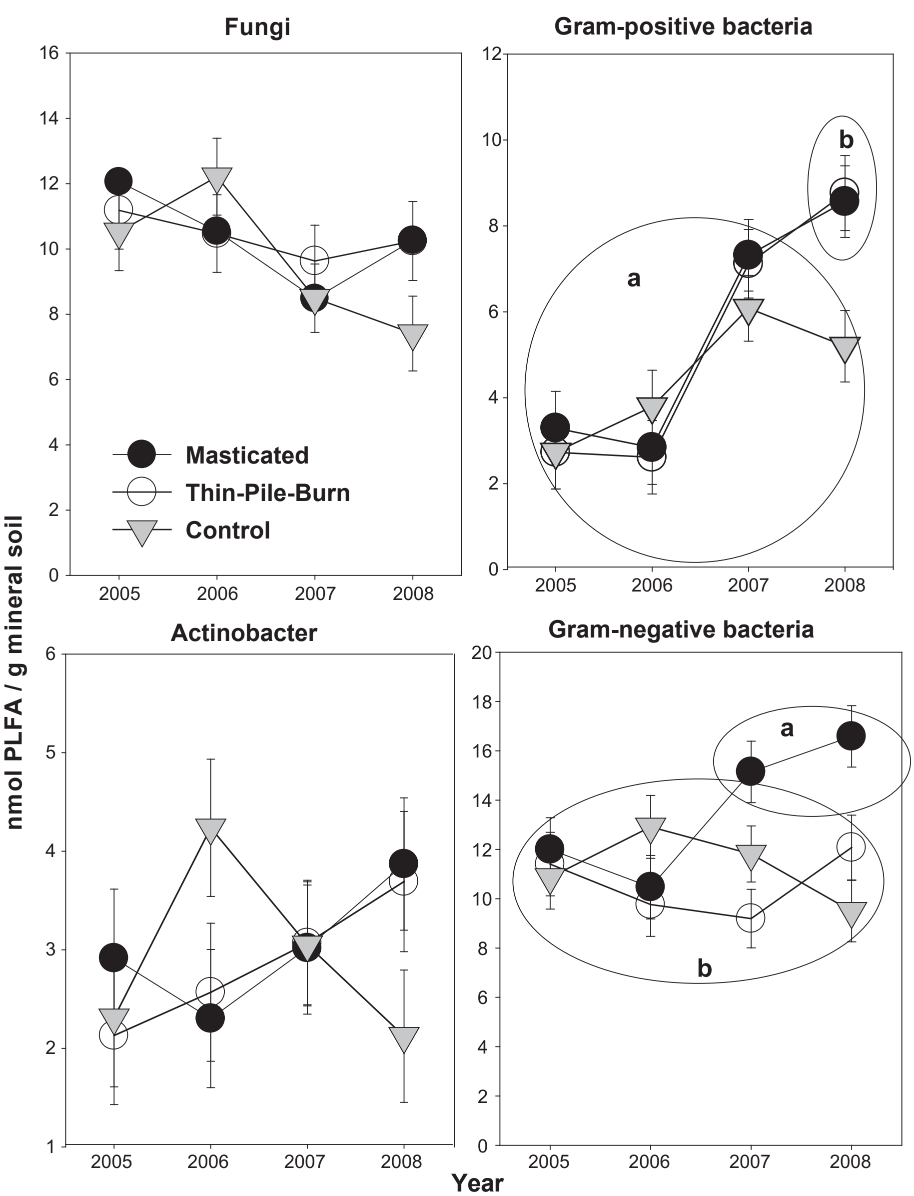

Fig. 2. Microbial mass based on composites of phospholipid fatty acids for mineral soil (0–5 cm) for a fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. Circled groups that do not share letters were significantly different at α = 0.05 significance level for treatment by year interactions. Panels without circle designates non-significance.

Table 7
Simultaneous pairwise comparisons using MRPP analysis of microbial composition based on phospholipid fatty acid determinations for fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. Ones represent the treatment pair for comparison with zero the excluded treatment.

	Mastication	Thin-Pile-Burn	Control	Agreement (A value)	*p* value
2005	1	1	0	−0.005	0.584
Pre-	1	0	1	−0.003	0.466
treatment	0	1	1	−0.003	0.497
2006	1	1	0	0.033	0.018
Post-	1	0	1	0.021	0.074
treatment	0	1	1	0.078	0.001
2007	1	1	0	0.134	< 0.001
Post-	1	0	1	0.105	< 0.001
treatment	0	1	1	0.057	0.012
2008	1	1	0	0.106	< 0.001
Post-	1	0	1	0.269	< 0.001
treatment	0	1	1	0.115	< 0.001

treatment when compared to the controls and thin-pile-burn treatments (Table 4). This difference in total C and N, and C:N ratios was not reflected in the mineral soil (Table 5). Soil pH at both mineral soil depths also did not significantly change for either fuel treatment (Table 5).

Total available inorganic N pool size measured by ion exchange resins (PRS probes) differed significantly among sampling periods ($p < 0.001$), but not treatments ($p = 0.13$) or treatment by year interaction ($p = 0.51$) (Table 6). The differences in sampling periods was driven by net nitrification (97% of total inorganic N pool). The growing season sampling periods (1 and 3), but not the final growing period (5), had the greatest available inorganic N pool size The two winter sampling periods were approximately half the values of the growing season available inorganic N pool size (Table 6). Our final sampling, three years post-treatment during the growing season, had the lowest total available inorganic N pool size among all time periods.

Fungal to bacterial ratios were significant for treatment by year interaction ($p = 0.044$). Grouping the PLFA biomarkers, we can see that fungi was not significantly different among treatments, but there was a decrease in fungal biomass overall with each successive sampling. By the second and third year post-treatment bacterial populations had significantly increased (Fig. 2). Overall total PLFAs differed for treatment × year interaction following treatment, except for the first post-treatment year between thin-pile-burn and control (Table 7).

The most consistent pattern in the correlation matrix of soil variables was the decrease in F:B ratios with each successive sampling period for all plots. Mastication microbial biomass increases correlated with successive sampling periods, and increased available inorganic N pool also was correlated with increased total C and N, and C:N ratios in the mineral soil. This correlation of increased available inorganic N did not present itself in the more rigorous statistical analysis. The pile-thin-burn plots available inorganic N pool was negatively correlated with increasing total C and C:N ratio of the mineral soil, yet as with the mastication treatment these results did not appear in the GLIMMIX model analysis (see Table 8).

4. Discussion

Microbial facilitated mineralization of N is an important yet complex ecosystem process (Schimel and Bennett, 2004). The use of available inorganic N pool size over time in the absence of plant roots provides an indicator of potential available plant N (Hart et al., 1994). We expected that the added C-rich inputs (~4 Mg C·ha^{-1}, C:N ratio of 27) from mastication would stimulate microbial growth and increase N demand thus immobilizing available inorganic N from the surface mineral soil (Schimel and Bennett, 2004) just as Rhoades et al. (2012) found with fresh masticated residues. During mastication some live shrubs were masticated, yet the majority of masticated material was from standing dead trees. Rhoades et al. (2012) showed that fresh mulch (1-y) gained the greatest amount of N through microbial translocation from mineral soil while older mulch (5-y) lost N during their study. Our study cores were a mixture of pre-treatment O-horizon with masticated material, which more closely resembled Rhoades et al. (2012) 5-y mulched residues. While available inorganic N pool size was reduced approximately 40% from growing season vs non-growing season for the first two years following fuels treatments as would be expected, the final growing season the available inorganic N pool was significantly less than the previous growing season and non-growing

Table 8
Pearson's correlation coefficients for mineral soil (0–5 cm) variables from a fuel reduction study in southwest Colorado, USA. Mastication and thin-pile-burn treatments done winter of 2005–2006. Coefficients with p values in parentheses for overall study represent the treatment pair for comparison with α < 0.05.

Variable	Year (2005–2008)	pH	Soil Moisture (%)	Litter Mass (Mg/ha)	Litter Carbon:Nitrogen	Soil Carbon (%)	Soil Nitrogen (%)	Soil Carbon:Nitrogen
Control								
Microbial biomass	−0.30	−0.43	0.11	−0.51	0.05	0.12	0.31	0.04
	(0.34)	(0.16)	(0.74)	(0.09)	(0.87)	(0.70)	(0.77)	(0.90)
Fungi:Bacteria ratio	**−0.72**	0.01	0.45	−0.19	−0.52	−0.52	−0.34	−0.44
	(0.01)	(0.97)	(0.14)	(0.56)	(0.08)	(0.08)	(0.27)	(0.08)
Nitrogen availability	−0.14	−0.34	−0.12	−0.30	0.37	0.22	0.20	0.14
	(0.66)	(0.09)	(0.69)	(0.34)	(0.21)	(0.49)	(0.54)	(0.65)
Mastication								
Microbial biomass	**0.56**	−0.14	−0.08	−0.02	−0.11	−0.37	−0.06	−0.50
	(0.06)	(0.66)	(0.81)	(0.94)	(0.74)	(0.23)	(0.85)	(0.10)
Fungi:Bacteria ratio	**−0.80**	0.25	0.34	0.12	−0.43	0.18	−0.03	0.24
	(< 0.01)	(0.43)	(0.29)	(0.71)	(0.16)	(0.58)	(0.94)	(0.46)
Nitrogen availability	−0.07	−0.24	0.01	0.27	0.22	**0.86**	**0.76**	**0.75**
	(0.83)	(0.45)	(0.98)	(0.40)	(0.50)	**(< 0.01)**	**(< 0.01)**	**(< 0.01)**
Pile-Thin-Burn								
Microbial biomass	0.40	−0.37	−0.38	−0.38	0.18	0.18	0.07	0.23
	(0.19)	(0.23)	(0.22)	(0.23)	(0.58)	(0.59)	(0.82)	(0.46)
Fungi:Bacteria ratio	**−0.84**	−0.18	0.48	0.30	−0.39	−0.03	0.31	−0.23
	(< 0.01)	(0.58)	(0.12)	(0.34)	(0.21)	(0.92)	(0.34)	(0.48)
Nitrogen availability	−0.20	−0.33	−0.39	0.16	0.12	**−0.69 (0.01)**	−0.42	**−0.69**
	(0.54)	(0.29)	(0.21)	(0.63)	(0.70)		(0.18)	**(0.01)**

seasons. The change in C:N ratios of the inputs at the micro-scale did not translate to a change at the larger scale of our sampling scheme, yet we still measured a short-term pulse of inorganic N potentially available for plant uptake during the second year following mastication treatment though not statistically significant. Young et al. (2014) reported higher inorganic N following mastication of juniper (*Juniperus osteosperma*) in a sagebrush (*Artemisia tridentata* var. *wyomingensis*) steppe ecosystem, which they attributed to reduced uptake by trees and an increase in available soil moisture. Young et al. (2014) found, as we did, that total soil C and N in the short-term did not respond to residue addition from mastication of trees. Slow decomposition due to the aridity of these sagebrush steppe communities was thought to be the reason for the non-response to organic residue additions. We speculate this reduction in available inorganic N pool size over time at our study sites was strongly influenced by the mortality event that occurred prior to implementation of this study confounding our treatment effects.

The addition of high C:N ratio organic matter resulting from mastication of standing dead trees and some live shrubs was presumed to favor fungi along with translocation of N from mineral soil into the O horizon. What we measured was a decrease in F:B ratio over time with an increase in bacteria in the mineral soil for both fuel treatments and the control. Mastication altered composition of the microbial population, yet did not alter the total mass of the microbial population based on PLFA analysis. We believe the primary factor in the increase in bacteria in the masticated areas was likely due to changes in microclimate (Meentemeyer, 1978). Rhoades et al. (2012), working at two of the same study sites, did show that soil temperature extremes, both high and low, were attenuated by thin mulching (2.5 cm) with little effect on soil moisture, while Owen et al. (2009) working in the same general region also found comparable temperature changes with increased soil moisture. Maximum soil temperatures were 15 °C cooler during summer months, while mean annual soil temperatures were 3.4 °C cooler (Rhoades et al., 2012). Winter temperatures for mulched sites were also warmer than their controls. The effects we saw to microbial populations may be due to the attenuation of winter minimum temperatures with more optimal summer conditions resulting in bacteria being favored in the mastication sites (Pietikäinen et al., 2005). Over the length of our study, effects at the thin-pile-burn sites were confounded by probable increases in soil temperatures extremes due to a dark surface during summer months and reduced insulation during winter months at the burn piles, favoring fungi, but an immediate post-treatment increase in available inorganic NH_4^+ favoring bacteria. Thin-pile-burn treatments not only altered the microbial composition favoring bacteria but decreased the total mass of the population by the third year following treatment. The mortality event was again a major confounding factor in interpretation of the microbial data as the F:B ratios declined with each successive sampling for both fuel treatment, but more importantly for the controls.

5. Management implications

Fire behavior in woodlands of southwestern United States has drawn considerable attention, yet the ecological response of these woodlands to both natural and man-made disturbance is not well understood or often considered (Floyd et al., 2004; Romme et al., 2009). Land managers often initiate actions to reduce potential fire hazards either by reducing fuels or altering fuel structure to modify fire behavior following events such as drought, insect outbreaks, or a combination. Mastication of standing dead and live trees and shrubs, as a fuels treatment, modifies fire behavior (Kreye et al., 2014), but is not without ecological consequences (Rhoades et al., 2012). Information on those consequences is very limited, especially with regards to semi-arid woodlands. Typically there is no commercial value in wood products from these semi-arid woodlands; therefore the whole tree is masticated and left on site. This differs from more mesic systems where the tree is harvested for a commercial product prior to mastication of harvesting residues.

Wildfire mitigation strategies that create resistance to future disturbances will necessitate treatment protocols that restore soil processes. The mastication residues from semi-arid woodlands at operational scales we studied did not significantly increase surface litter mass. Soil carbon additions in the form of masticated trees has been shown to increase soil moisture and reduce soil temperature, and show both positive and negative effects on plant available nitrogen (Miller and Seastedt, 2009; Owen et al., 2009; Rhoades et al., 2012). Contrary to the "classic" model for mineralization of high C:N ratio organic matter (Paul and Clark, 1996), the addition of C rich inputs to the surface organic horizon does not automatically mean N immobilization in the mineral soil. Short-term increases in available N can occur demonstrating the complex nature of decomposition and mineralization processes (Kaiser et al., 2014). Previous research has found that soil responses from combining thinning and fire treatments are not simple additive effects of the individual treatment effects. The spatially variable nature of prescribed fire often confounds treatment effects. Fire generally showed small and random effects on soil properties and processes. Our results follow what others have found in more mesic coniferous forests that total C and N in the mineral soil is relatively insensitive to fuel reduction treatments (Boerner et al., 2009; Overby and Hart, 2016). A major confounding issue with interpretation of results from this study is the ecological effects created by a severe regional drought and insect infestation (Clifford et al., 2008). The addition of carbon to the soil has been shown to promote native herbaceous plant cover and diversity in a pinyon-juniper community (Brockway et al., 2002), yet addition of woodchips has also been shown to reduce understory plant richness, diversity and cover, while increasing nonnative species cover and altering plant community composition in different ponderosa pine forests (Miller and Seastedt, 2009; Wolk and Rocca, 2009). In contrast, Kane et al. (2010) found that masticated treatments increased both native and nonnative plant cover and density. Studies that investigate basic ecology following such mortality events would be extremely helpful to researchers and managers as they develop management actions following such mortality events. Mastication as a cost effective wildfire mitigation technique has become more widely accepted, yet more research is needed to consider how managed additions of low quality organic residues alters abiotic conditions and soil microbial populations that mediate decomposition and mineralization processes.

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