EFFECTS OF POST-FIRE SOIL HYDROPHOBICITY ON INORGANIC SOIL NITROGEN AND SULFUR CYCLING

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ABSTRACT

Fire plays an important role in many native ecosystems, and its suppression has increased woody encroachment across the globe. Restoring native herbaceous communities following fire in encroached systems is often challenging. Post-fire soil hydrophobicity is one factor that may further limit site restoration by limiting soil moisture, which may in turn affect soil nutrient dynamics. We conducted a field study in a burned pinion-juniper woodland to understand the effects of post-fire soil hydrophobicity on soil moisture and soil nutrients. Plots centered on *Juniperus osteosperma* or *Pinus monophylla* trees were either left untreated or treated with a surfactant to ameliorate soil hydrophobicity, and then left bare or seeded with *Pseudoroegneria spicata*. Measurements were taken two years after fire in May, by which time the surfactant treatment had 124.4% higher soil water content than the repellent control. This effect was a function of a thick, hydrophobic layer in the control as compared to hydrophilic soil conditions when treated with surfactant after the fire. Soil nutrient levels were 45.5%, 37.8%, and 52.3% lower in the surfactant treatment compared to the repellent control for sulfate, nitrate, and ammonium respectively. The development of restoration tools and practices to manage these effects of soil hydrophobicity may help reduce invasive species and facilitate the establishment of desired native herbaceous communities.

INTRODUCTION

Fernelius (2013) reviewed how altered fire regimes can have devastating effects on native ecosystems. Anthropomorphic fire suppression has increased woody encroachment worldwide over the past century. When fires occur in these encroached systems, they often become more severe. This increased severity can cause further ecosystem degradation by decreasing microbial communities, and increasing soil erosion and weed invasion. While fire can destabilize woody encroached systems, it also gives native grass systems an opportunity to reestablish. Post-fire soil hydrophobicity is one factor that may limit site restoration by altering soil-water interactions.

Soil hydrophobicity is a soil condition caused by hydrophobic organic compounds binding to soil particles, which delays water infiltration longer than 5 seconds. Soil hydrophobicity decreases water infiltration and percolation, which consequently increases surface runoff after fire. Such increased runoff may decrease surface moisture levels as water moves gravimetrically toward more hydrophilic soils.

Post-fire soil hydrophobicity, by decreasing soil moisture, may alter soil nutrient dynamics. Following fire, burned woody mound "fertile islands" contain high soil nitrogen (N) levels relative to the surrounding interspace (Vitousek and Matson 1985; Klopatek 1987; Hibbard et al. 2001). Although the creation of sulfur (S) islands of fertility may not occur (Cross and

Schlesinger 1999), inorganic S levels do increase following fire (Vlamis and Gowans 1961). While studies have shown soil hydrophobicity to increase erosion and therefore nutrient loss and redistribution (Ravi et al. 2009), soil hydrophobicity may actually increase nutrient retention within the hydrophobic zone. Low moisture conditions limit water-dependent N and S cycling processes, such as immobilization and leaching (Bhardwaj and Novák 1978; Eriksen et al. 1998; Ketterings et al. 2003; Austin et al. 2004). By inhibiting water infiltration (and soil wetting), hydrophobicity may therefore prolong nutrient retention within woody islands of fertility.

The objective of this study was to identify the effects of post-fire soil hydrophobicity on soil nutrient cycling.

MATERIALS AND METHODS

Research was conducted on the Ray May Fire near Reno, Nevada. This pinion-juniper woodlands fire occurred during August 2011. From the time the fire finished burning in August 2011 to the end of the August 2012 sampling, the site received 73.1mm of precipitation. From the August 2012 sampling to the August 2013 sampling, the site received 126.6mm of precipitation. Average precipitation is 225.5 mm

The experiment was installed as a randomized complete block design with seven blocks confined to a two-acre area of the fire. Each block contained four mature trees (i.e. tree age greater than 50 years) of either *Pinus monophylla* (Torr. & Frém.) singleleaf piñon or *Juniperus osteosperma* (Torr. Little) Utah juniper. Each tree subcanopy comprised one 1.5 m radius plot. Treatments were assigned in factorial combination to trees within each block and included (1) control (water) or surfactant treatment (to ameliorate soil hydrophobicity) and (2) unseeded (bare) or seeded with *Pseudoroegneria spicata* (bluebunch wheatgrass). Each tree randomly received one of these four treatments.

In order to ameliorate soil hydrophobicity, the nonionic surfactant ACA2045 (Aquatrols, New Jersey, USA) was applied to surfactant plots. A concentration of 1.47 (v/v) surfactant active ingredient was identified and selected as the lowest active ingredient concentration needed to penetrate the hydrophobic layer in under 5 s using the WDPT test. The volume of applied surfactant was enough to saturate the ash and hydrophobic layers, which was determined to be 113.6 L per plot. Following surfactant application, an additional 19.0 L of water was applied to each plot to wash the surfactant from the surface and prevent potential toxicity issues for the seeds. The remaining non-surfactant treatment plots were treated with an equal volume of water.

Following surfactant and water application, plots were seeded with *P. spicata* at 25 kg ha^{-1} PLS and were raked to bury the seed just below the soil surface.

Plots were sampled two years later in the spring (May). Response variables chosen to assess treatment effects included *in-situ* measurement of hydrophobic layer thickness. Soil samples were collected for 2-4 cm below the bottom of the ash layer. These samples were transported back to the lab to assess *ex-situ* actual hydrophobicity severity, gravimetric soil water content (air-dried for 72 h), and soil nitrate-N, ammonium-N, and sulfate-S.

Actual soil hydrophobicity severity was assessed using the WDPT test. Under this test, soils were considered hydrophobic if infiltration was delayed longer than 5 s. The test was performed using five 95 µl water droplets per sample. Nitrate and ammonium were extracted from soils using a 2 M KCl solution and analyzed using a LACHAT Flow Injection Autoanalyzer (LACHAT 1994). Sulfate was extracted from soils using a monocalcium phosphate solution (Fox et al. 1964) and were analyzed using inductively coupled plasma spectroscopy (Iris Intrepid II XSP, ICP-OES, Thermo Electron Corporation, Waltham, MA, USA).

Data were analyzed using SAS software version 9.3 (SAS Institute Inc. Cary, NC). Mixed model analysis was used to analyze gravimetric soil water content, soil sulfate, soil nitrate, soil ammonium, and hydrophobicity severity and thickness. Block was considered random while soil treatment and seed treatment were considered fixed factors. To account for zero values, a constant (1) was added to the measured values, and all data were log-transformed before analysis. Mean values were separated using the Tukey-Kramer honestly significant difference multiple-comparison method. Differences were considered significant when $P < 0.05$.

RESULTS

Hydrophobicity severity was influenced by soil treatment and not by seed treatment or their interaction (Table 1). Average severity levels for the surfactant treatment were below 5 s, qualifying the surfactant-treated soils as hydrophilic and the controls (water applied without addition of surfactant) remained hydrophobic (Fig. 1a).

The thickness of the hydrophobic later was influenced by soil treatment, but not by seed treatment or their interaction (Table 1). However, seed treatment was nearly significant (P = 0.0834). Hydrophobic control soils and surfactant-treated soils were statistically different (Fig. 1b). Application of a surfactant thus decreased soil hydrophobicity severity and thickness, while the water-treated plots remained severely hydrophobic.

Soil water content levels were influenced by soil treatment and layer, but not by seed treatment or their interactions (Table 1). Differences were significant, with 124.4% greater levels in the surfactant treatment (Fig. 1c). The 2-4cm layer exists within the hydrophobic layer.

Analysis showed inorganic N to not be influenced by species (nitrate P = 0.7189; ammonium P = 0.9464). For this study, all soil nutrients were therefore combined by species treatment. Soil sulfate samples were combined by species treatment prior to sulfate analysis.

Soil sulfate, nitrate, and ammonium were influenced by soil treatment (Table 2). Soil nutrient levels were 45.5%, 37.8%, and 52.3% lower in the surfactant treatment compared to the repellent control for sulfate, nitrate, and ammonium respectively (Fig. 2).

DISCUSSION

We significantly reduced soil hydrophobicity levels in the surfactant-treated plots. A previous study, which used the same surfactant chemical and grass species as this study, indicated that the surfactant has neither negative nor beneficial effects on seedling germination and establishment, after controlling for amelioration effects (Fernelius 2013).

Our soil moisture results showed that ameliorated post-fire soil hydrophobicity with a surfactant to increase soil moisture in the repellent zone. This is consistent with previous research, which has also shown ameliorating soil hydrophobicity to increased soil moisture (Osborn et al. 1967; Krammes and Osborn 1969; DeBano and Conrad 1974; Madsen et al. 2012).

Although less research has been performed on the effect of fire on S than on N, both are similar in their cycling processes (Debano 1991), so some level of similarity in response was expected. Fire increases soil inorganic levels for both of these nutrients directly after fire (Vlamis and Gowans 1961). Generally these heightened levels are short lived (Wan et al., 2001; Certini 2005), but our research suggests that hydrophobic soils may retain elevated levels longer than hydrophilic soils for all three measured nutrients. Differences in nutrient levels between hydrophobic and hydrophilic soils were likely driven by differences in microbial and plant immobilization, which in turn were driven by differences in soil water content between the two soil treatments. Because S is primarily cycled through microbe-influenced processes (Eriksen et al. 1998), decreasing microbial activity likely also decreases S cycling processes such as mineralization, immobilization, oxidation, and reduction. Likewise, N cycling is also heavily mediated by microbial activity through processes such as mineralization, immobilization, nitrification, and denitrification (Ketterings et al. 2003).

One consequence of these altered nutrient dynamics may be an increase in weed invasion following hydrophobicity dissipation. While these data do not investigate the effects of elevated nutrient levels in hydrophobic soils on weed invasion, increased weed invasion following fire has been well documented (Dukes and Mooney 1999; Ott et al. 2001; Esque et al. 2010) and is generally attributed to the increase in unused resources found after fire (Davis et al. 2000; Lowe et al. 2003). Following the dissipation of the hydrophobic layer several years after fire, high nutrient levels may become available to nutrient-exploiting invasives (Huenneke et al. 1990; Burke and Grime 1996), facilitating their establishment.

CONCLUSIONS

This study identifies soil hydrophobicity as one factor that may limit native plant reestablishment after fire in woody encroached systems through its influences on soil moisture and soil nutrient cycling. As humans continue to suppress natural fire regimes and as woody plants continue to encroach, it will be important to understand the mechanisms controlling native plant reestablishment after fire in order to facilitate the development of restoration tools and management practices.

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Table 1. Results of mixed ANOVA models for soil hydrophobicity severity and thickness, and gravimetric soil water content by soil treatment, seed treatment, and their interaction.

	Severity		Thickness		Water content	
	F	*P*	*F*	*P*	*F*	*P*
Soil treatment	88.53	**<0.0001***	6.60	**0.0168**	9.45	**0.0065**
Seed treatment	2.11	0.1640	3.26	0.0834	0.05	0.8252
Soil × Seed	0.03	0.8586	0.01	0.9378	0.38	0.5453

* Significant factors (P < 0.05) are highlighted in bold

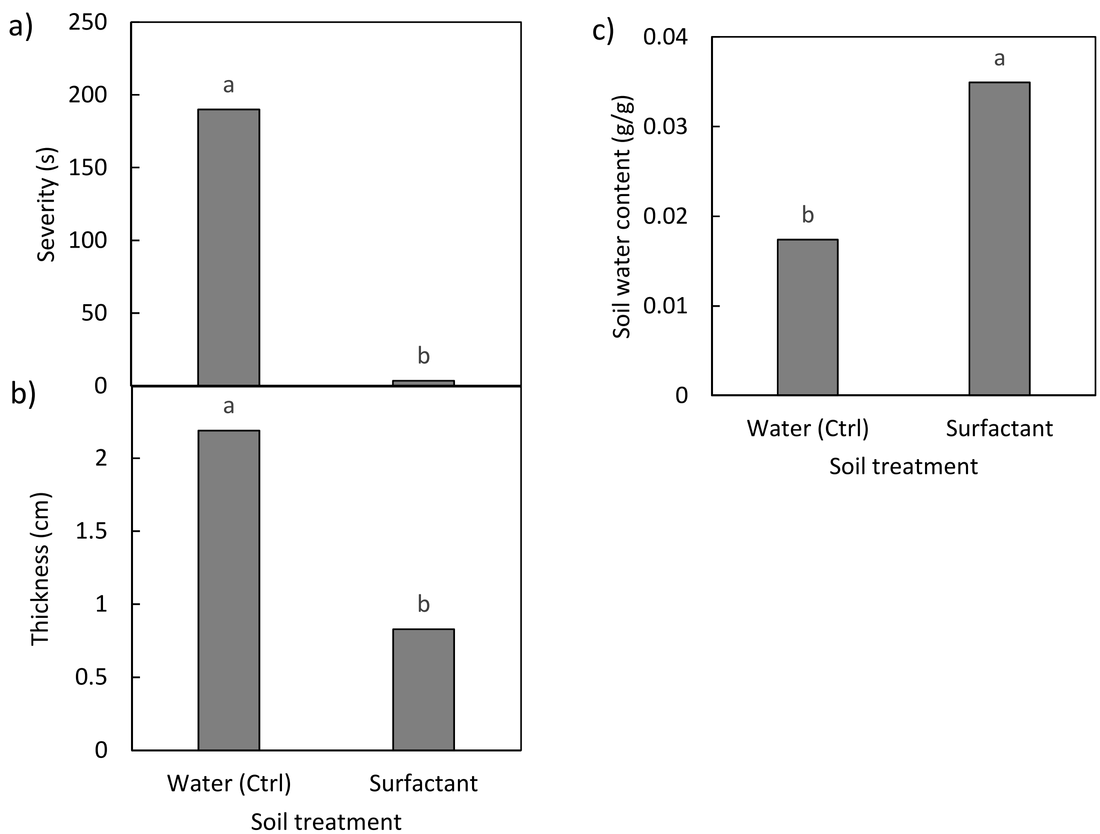

Figure 1. (a) Soil hydrophobicity severity, (b) hydrophobicity thickness and (c) gravimetric soil water content for both soil treatments (surfactant and water) in May of the second year after fire. Values are means, with unique letters indicating significant differences between soil treatments ($P < 0.05$).

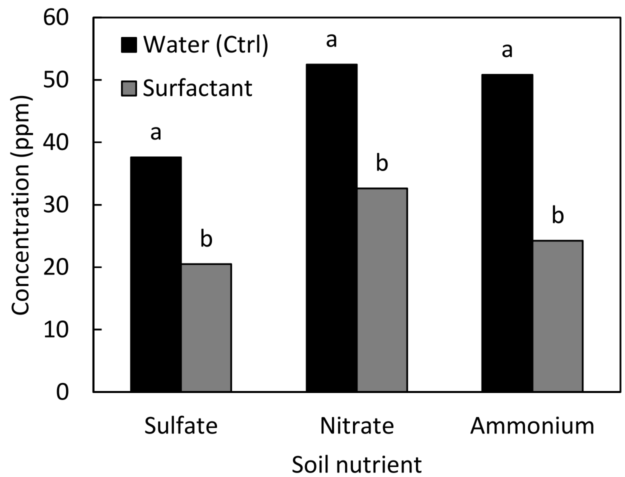

Figure 2. Soil nitrate and soil sulfate levels for both soil treatments (surfactant and water) measured in May of the second year after fire. Soils were sampled 2-4 cm from the bottom of the ash layer. Values are means, with unique letters indicating significant differences between soil treatments within each nutrient ($P < 0.05$).

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