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Post-fire Interactions Between Soil Water Repellency, Islands of Fertility, and Bromus tectorum Invasibility

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ABSTRACT

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and *Bromus tectorum* Invasibility

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An intrinsic link exists between soil moisture and soil nitrogen. Factors that increase or decrease soil moisture can have a profound effect on soil nitrogen cycling, which may have later repercussions in the plant community. Post-fire soil water repellency is one factor that can limit soil moisture acquisition and may indirectly affect nitrogen cycling and weed invasion in woody islands of fertility. Plots centered on burned *Juniperus osteosperma* trees were either left untreated or treated with a surfactant to ameliorate water repellency. Two years later, soils were excavated from the untreated and treated field plots. In the greenhouse, half of each soil type received a surfactant treatment while the other half was left untreated. Pots were seeded with either *Bromus tectorum* or *Pseudoroegneria spicata*. Analysis of field soil prior to the greenhouse trial showed that untreated, repellent soils had inorganic nitrogen levels an order of magnitude higher than wettable, surfactant-treated soils. Greenhouse pots that had received a surfactant treatment in the field and/or greenhouse had similar soil water content, plant density, and above ground biomass, which were, respectively, 55-101%, 31 to 34 -fold, and 16 to18 -fold greater than pots without a surfactant treatment. No species effects were found. This study indicates that water repellency can reduce wetting and retention of water in the soil while promoting the retention of high levels of inorganic nitrogen. However, the effects of soil water repellency on inorganic nitrogen appeared to have a minimal effect on plant growth compared to the effect of soil water repellency on water availability.

Keywords: *Bromus tectorum*, island of fertility, nitrogen, soil hydrophobicity, soil moisture, surfactant, water repellency, wildfire

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Post-fire interactions between soil water repellency, islands of fertility and *Bromus tectorum* invasibility

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1. INTRODUCTION

Soil water repellency, a soil condition evident in a variety of woody systems worldwide (Doerr *et al*., 2000), may limit ecosystem recovery after fire. Generally formed in the woody mound zone (area directly occupied by the plant after fire) (Zvirzdin, 2012), soil water repellency decreases water infiltration and percolation in the soil (Robichaud, 2000; Wang *et al*., 2000; Madsen *et al.,* 2011), which can decrease soil water contents (Madsen *et al*., 2012). As woody plant encroachment increases in arid and semiarid systems worldwide, soil water repellency may become an increasingly influential factor in site recovery after disturbances, like fire and fuel reduction treatments, through its impacts on soil moisture.

In addition to soil water repellency, woody vegetation also forms "islands of fertility" (Garcia-Moya and McKell, 1970). Before fire, woody vegetation increases nutrient resources and increases soil water content in the tree mound zone, thus forming fertile islands below and immediately surrounding the plant (Dunkerley, 2000; Hibbard *et al*., 2001; Eldridge and Freudenberger, 2005; Huxman *et al.,* 2005; Esque *et al*., 2010). During periods when soil water is available for plant growth, nitrogen is generally the most limiting resource in arid and semi-arid systems (Lauenroth *et al*., 1978; Sharifi *et al*., 1988; Hooper and Johnson, 1999; Krueger-Mangold *et al*., 2004). Long periods of fire exclusion can result in nitrogen-limiting conditions as plants and microbes take up soil nitrogen and hold it in an organic form (Covington and Sackett, 1986). Within fertile islands, available nitrogen often increases directly following wildfires (Wan *et al*., 2001). Fire increases inorganic forms of nitrogen, (ammonium NH_4–N and nitrate NO_3–N) directly through combusting organic matter (Christensen, 1973; Christensen and

Muller, 1975; McNabb and Cromack, 1990) and indirectly by creating environmental conditions that speed microbial decay processes (Choromanska and DeLuca, 2002).

The coexistence of soil water repellency and fertile islands under woody vegetation may cause high nutrient levels to persist longer in the soil. Typically, elevated post-fire soil nutrient concentrations are short-lived (Wienhold and Klemmedson, 1992; Gimeno-García *et al*., 2000; Wan *et al*., 2001; Certini, 2005). However, the reduction of soil water content by soil water repellency may limit the downward movement of nitrogen in water repellent soils. Within the water repellent layer, infiltration and percolation can be inhibited (Madsen *et al.,* 2011), which limits soil water acquisition by plants and microbes and may limit water-influenced processes such as nitrogen cycling and leaching (Austin *et al.,* 2004). Ameliorating soil water repellency increases soil water content in surface (DeBano & Conrad 1974; Osborn et al. 2001) and water repellent soil layers (Madsen et al., 2012). Specific steps in the soil nitrogen cycle that may be inhibited by dry conditions include nitrification (Maag and Vinther 1996; Dijkstra *et al.* 2012), immobilization by plants (Barber 1995; Dijkstra *et al.*2012) and soil microbes (Bhardwaj and Novák 1978; Dijkstra *et al.*2012), denitrification (Sexstone *et al.* 1985; Maag and Vinther 1996), and mineralization (Dijkstra *et al*.2012). Although there is some indication that soil water repellency can promote leaching through non-repellent preferential flow paths (Ritsema and Dekker, 1996; Robinson, 1999; Stites and Kraft, 2001; Aamlid *et al*., 2009), research on the nutrient dynamics within the repellent portions of the soil is lacking. We hypothesize that hydrologic impairment limits nitrogen loss within the water repellent layer by reducing soil nitrogen cycling and leaching, thus lengthening the persistence of islands of fertility in the tree mound zone after disturbance.

Such effects of soil water repellency on soil nutrient retention in islands of fertility may have a subsequent influence on post-fire vegetation establishment patterns. While soil water repellency can initially inhibit seedling establishment, its dissipation months to several years after the fire allows soil water contents to increase in the water repellent zone and may allow biota (e.g. plants and soil microbes) access to high levels of soil nitrogen. Such surplus resources can facilitate weed invasion (Davis *et al*., 2000). Invasibility can be explained in part by resource fluctuations; whenever resource supply increases relative to demand, invasibility will increase (Lauenroth *et al*., 1978; Davis *et al*., 2000). The invasive success of *Bromus tectorum* L. (cheatgrass) and many other weeds in arid and semi-arid systems is partially due to their ability to quickly exploit periods of surplus resources and thereby outcompete native species, whose maximum growth rates occur at lower nutrient levels (Burke and Grime, 1996; Lowe *et al*., 2003; Vasquez *et al*., 2008; Esque *et al.,* 2010). Following fire in arid and semi-arid forest communities, the burned tree mound zone can be especially vulnerable to weed invasion, as has been observed with the invasion of *B. tectorum* in burned woodlands with *Pinus* spp. (piñon) and *Juniperus* spp. (juniper) (Tausch *et al.,* 1995; Ott *et al*., 2001). Relative to the surrounding interspaces, these zones typically have a greater abundance of available resources as islands of fertility (Klopatek *et al*., 1990). As soil water repellency dissipates after fire, allowing soil water contents in the water repellent layer to increase, we anticipate that the elevated nitrogen concentrations in the tree mound zone will become available to plants and promote exotic weed invasion.

The objectives of this study were to (1) clarify the role of soil water repellency in influencing soil water availability and subsequent soil nitrogen cycling and (2) verify if the conditions created by soil water repellency favor *B. tectorum* emergence and growth compared to the native perennial bunchgrass *Pseudoroegneria spicata* (bluebunch wheatgrass). We hypothesized that soil water repellency would limit soil water contents while limiting nitrogen loss and seeding establishment. Upon dissipation of the repellent zone, these conditions would favor the establishment of *B. tectorum* over the native perennial species studied.

2. Materials and Methods

2.1 Field soil preparation and soil collection

Soil used in this study was collected from the 2007 Milford Flat wildfire, at a location 13.7 km, NE of Milford UT, USA (Lat: 38° 26' 12" N, Long: 112° 51' 46" W) at the base of the Mineral Mountain Range in March 2010. Madsen *et al*. (2011) report a detailed description of the study site. Mean annual precipitation was 370 mm (PRISM Climate Group, 2009). Soil is a coarse sandy loam, mixed, mesic Aridic Haploxeroll, with a 7.4 pH. Prior to the fire, the vegetation community was a piñon-juniper woodland of Phase III encroachment (heavily-infilled) into sagebrush (*Artemisia* L.) steppe (Miller *et al.* 2008), with *Pinus monophylla* (Torr. & Frém.) singleleaf piñon and *Juniperus osteosperma* (Torr.) Little Utah juniper acting as the primary vegetation influencing ecological processes on the site.

In May 2008, 10 circular, 4 m diameter field plots were established; each plot was centered on the trunk of a burned *J. osteosperma* tree. Five of the 10 trees were randomly chosen to be hand sprayed with the nonionic surfactant ACA2045 (Aquatrols, New Jersey, USA), which is a blend of alkylpolyglycoside (APG) and ethylene oxide/propylene oxide (EO/PO) block copolymers. The surfactant was applied at 0.12 L active ingredient m^{-2} with 120 L m^{-2} of water.

The remaining five trees served as the control and were treated with water only at the same rate. In March of 2009, surfactant was reapplied at the same rate as the previous year.

In March of 2010, soil was sampled for nitrogen analysis and severity of water repellency. After samples were collected, soil for a greenhouse study was excavated from each plot, from three distinct layers associated with water repellency: (1) the upper hydrophilic layer, composed primarily of ash, (2) the underlying water repellent layer (or previously water repellent for surfactant-treated plots), and (3) the lower hydrophilic layer, found immediately below the water repellent zone (<20 cm in depth). Sampling depth for repellent plots was determined using the water drop penetration time (WDPT) test (Bisdom *et al.*, 1993) at 5 seconds or greater. Surfactant-treated plots were sampled at depths to repellent plots for all layers. To reduce variability in water repellency, hydrophilic patches were excluded when excavating soil from plots treated with water only. Soil collected from each tree was analyzed for NO_3–N and NH_4–N using a QuikChem® 8500 Flow Injection Autoanalyzer (LACHAT, 1994).

2.2 Greenhouse trial

2.2.1 Study design

Greenhouse research was conducted at the Eastern Oregon Agricultural Research Center, Burns, OR, USA, using soil collected in the field trial. Within each distinct soil layer and treatment we mixed the excavated soil to create homogenous soil. We placed soil from the three distinct layers into 20.3 cm diameter pots made from PVC pipe in the same order as found in the field. We filled pots sequentially with 10.0 cm of soil from the lower hydrophilic layer, 10.0 cm from the water repellent layer and 1.5 cm from the ash layer.

The experimental design of this trial consisted of two seeded species and four soil treatments, within seven randomized complete blocks (2 species x 4 soil treatments x 7 blocks = 56 pots). Study species include the native perennial, *P. spicata* and the invasive annual, *B. tectorum*. *Pseudoroegneria spicata* was chosen for comparison with *B. tectorum* due to its common use in reseeding western US rangelands after wildfire. We seeded each pot with *P. spicata* or *B. tectorum* at 20 PLS per pot. Seeds of *P. spicata* were purchased from Granite Seed Company, Utah, USA. *Bromus tectorum* seed was collected 1.5 km from the soil collection area.

The four soil treatments were generated by subjecting half of the untreated field soils and half of the surfactant-treated field soils to a surfactant treatment in the greenhouse. Pots treated with surfactant in the greenhouse received the same application rate as that applied previously in the first field application. The second half of the soils not treated with surfactant in the greenhouse were treated with an equivalent amount of water. The result of this additional treatment was four unique treatments, i.e. soil that was: (1) not treated with surfactant in the field or greenhouse and therefore was water repellent at the start of the greenhouse trial (no-surfactant: NS); (2) not treated with surfactant in the field and subsequently treated with surfactant at the start of the greenhouse trial (SG); (3) treated with surfactant in the field two years prior to field soil collection and not retreated with surfactant in the greenhouse (SF); and (4) treated with surfactant two years prior, and at the start of the greenhouse trial (SF+SG); (Table 1).

These four treatments allowed us to quantify how post-fire water repellency influences water content and nitrogen responses within the soil, and how those responses subsequently affect seedling emergence and plant growth. Specifically, the soil surfactant in the SG treatment allowed us to eliminate the effect that water repellency has on the soil's ability to wet and retain water. Wetting of the soil with the SG treatment may also allow access to available nitrogen that had been previously retained within the water repellent soil. Therefore, increased plant growth in the SG treated soil over the NS soil would be a function of both increased soil water availability and access to available nitrogen. A comparison of SG and SF treatments allowed us to quantify the degree that plant growth was influenced by increased access to available nitrogen. This comparison was possible because (1) the soil was wettable in both treatments, and (2) the elevated post-fire nitrogen levels had subsided in the SF treatment but remained high in the SG treatment (Table 1). A comparison of SF and SF+SG treatments allowed us to determine, independent of water repellency, any effects the surfactant chemicals may have had on water content, nitrogen, and plant responses. This was possible because both soils were wettable prior to the greenhouse study, but the SF treatment likely retained minimal levels of the surfactant chemicals compared to the SF+SG treatment, which received a surfactant treatment at the beginning of the greenhouse trial.

Throughout the study, pots were watered with a mist sprinkler system at a rate of 2.7 cm hr^{-1}. For pots designated to receive a surfactant treatment, the chemical was applied during the first watering, at the same rate as applied previously in the field, with the same ratio of water as a carrier (1508 ml of surfactant solution pot^{-1}). The remaining pots were treated with the same amount of water. To encourage seed germination and emergence, over the next 7 days pots were watered daily with 20 ml of water. For the remainder of the study, pots were given 400 ml of water every 7 days.

The study was conducted for 66 days after seeding from (8 July 2011 – 12 September 2011). During this time, the photoperiod ranged from 14 h 8 min (at the start of the study) to 11 h 4 min (at the conclusion of the study). Average light intensity between 1000 and 1600 h was 1333 mmol m^{-2} s. Air temperature averaged 14.6°C.

2.2.2 Measurements

Response variables chosen to assess treatment effects included: 1) runoff and leachate volume; 2) volumetric soil water content; 3) NO_3–N and NH_4–N loss through runoff and leachate; 4) soil NO_3–N and NH_4–N at the time of harvest; 5) seedling density; and 6) above and below-ground biomass. Leachate was collected by transforming the pot into a zero-tension lysimeter. The lysimeter was created by sealing the bottom of each pot and installing a drain hole connected to a collection bottle by a 4.8 mm silicon tube. Pots were placed on a 15° angular bench to promote runoff, which was collected from a 19 mm spout placed so the center was at the soil surface. To prevent seed and soil loss, pebbles 5-10 mm in diameter were placed in front of the spout. Runoff and leachate were collected after each watering. These samples were added into a cumulative sample for each treatment by block, for a total of 112 cumulative water samples (8 treatments x 7 blocks x 2 water loss points (i.e. runoff and leachate)). Volumetric soil water content was continuously recorded for all pots, in five of the blocks, at 2 cm below the ash layer using EC-5 Soil Moisture Sensors in conjunction with Em5b data loggers (Decagon Devices, Pullman, WA, USA). Total leachate and runoff samples were frozen and then at the conclusion of the study analyzed for NO_3–N and NH_4–N with a QuikChem® 8500 Flow Injection Autoanalyzer (LACHAT, 1994).

Prior to filling the pots, the severity of the water repellent soil was tested with the water drop penetration time (WDPT) test (Bisdom *et al.*, 1993) on five randomly collected samples from both water and surfactant treated field soils. In the procedure, five 95µl drops were placed on the soil surface and the time to water penetration was measured.

At the time of harvest, soil NO_3–N and NH_4–N levels were retested. Samples for these measurements were separately obtained within each pot from the ash layer, the underlying water repellent layer (0-9 cm below the ash layer), and the subsoil layer below the water repellent zone (12-21 cm below the ash layer). Total inorganic soil nitrogen was calculated by adding values for soil NO_3–N and NH_4–N together for each sample.

Plant density was measured throughout the study by recording the number of live seedlings every 3 days. At harvest, roots were washed free of substrate and below-ground and above-ground biomass (dried at 65°C for 72 hrs) were measured.

2.2.3 Data analysis

Data were analyzed using SAS software version 9.3 (SAS Institute Inc. Cary, NC). Mixed model analysis was used to analyze total runoff and leachate, loss of NO_3–N and NH_4–N through runoff and leachate, volumetric soil water content, soil NO_3–N, soil NH_4–N, total inorganic soil nitrogen, final seedling density, above-ground biomass, and below-ground biomass. Blocks were considered random while soil treatment, species and soil layer were considered fixed factors. A constant (1) was added to the measured values, including zeros, and subsequent values log-transformed before analysis. Mean estimates were separated using the Tukey-Kramer honestly significant difference multiple-comparison method. Differences were considered significant when $P < 0.05$. For soil nitrogen measurements, three-way interactions between soil treatment, species, and soil layer were included in all initial models, but in order to form simpler models, were dropped when not found to be significant.

3. Results

3.1 Field soil

3.1.1 Water drop penetration time (WDPT)

Prior to greenhouse treatment, soils not treated with surfactant in the field averaged 1.48 ± 0.17 s within the repellent layer. Surfactant-treated field soils, on the other hand, had WDPT values all below 5 seconds within the same layer. Application of a surfactant thus overcame water repellency in the repellent layer.

3.1.2 Soil NH_4–N and NO_3–N

Minor differences in NH_4–N levels were detected between soil layers (Table 2; Fig. 1a); there were no significant differences for this form of nitrogen among soil treatments (Table 2). Soil layer, soil treatment, and their interaction were all significant for NO_3–N (Table 2). The water repellent layer of the untreated soil held high levels of NO_3–N (Fig. 1b). The surfactant treatment lowered soil NO_3–N in the water repellent layer to 95% less than that measured in the untreated soil. Soil NO_3–N did not differ between treatments in the ash and subsoil layers.

3.2 Greenhouse trial

3.2.1 Runoff, leachate and soil water content

Total runoff from soil treated with surfactant was 71-85% lower compared to soil not treated with surfactant. This was consistent for soils treated with surfactant in the field or greenhouse (Tables 3 and 4). The amount of leachate was minimal and was not significantly influenced by field or greenhouse soil treatments (Tables 3 and 4). Soil water content response was similar to that seen for runoff (Table 3); average values over the period of the study were 1.8-fold higher in the surfactant-treated soils than in the no-surfactant soil (Table 4).

3.2.2 Runoff Water inorganic nitrogen

The amount of NO_3–N lost through runoff was influenced by field and greenhouse treatment, or both, but not by species (Table 5). The non-surfactant soil treatment had 2.6 to 5.5 -fold greater loss of NO_3–N through runoff than the surfactant-treated soils (Fig. 2a). This difference was largely driven by the high amount of runoff in the no-surfactant treatment compared to the surfactant treatments (Table 4). The irrigation water was measured to have a concentration of 0.87 mg L^{-1} NO_3–N ± 0.04 SE, which resulted in each pot receiving 2.23 mg NO_3–N via irrigation water by the end of the study, which may have accounted for much of the NO_3–N found in the no-surfactant soil runoff. Soil NO_3–N lost through leachate was not influenced by field treatment, greenhouse treatment, species, or their two-way interactions (Table 5). The lack of significant differences is probably due to the limited and varied amount of leachate among the pots, although the SG treatment did have on average 3-fold more NO_3–N loss than the other soil treatments. Of the pots that had more than 20 ml cumulative leachate, there was 172 % more leachate in the NS than the SG treatment (171.5 ± 36.7 ml, and 63.0 ± 34.3 ml, respectively). However, of these pots, the SG treatment lost 127% (7.7 mg/pot) more NO_3–N than the NS soil (3.4 mg/pot) through the leachate.

3.2.3 Soil NH_4–N, NO_3–N, and total inorganic nitrogen

At the conclusion of the greenhouse trial, soil NH_4–N levels were influenced by field treatment, greenhouse treatment, soil layer, and their two-way interactions (Table 3). In the water repellent layer, NH_4–N levels were 42.7% lower in the SG treatment than the NS treatment. In this same layer, SF and SF+SG treatments were similar to each other for NH_4–N, and 61-67% lower than the SG treatment (Fig. 3a). The application of soil surfactant in the greenhouse did not affect NH_4–N levels in the ash and subsoil layers. On average, NH_4–N levels in the NS and SG treatments were 140% higher than in the SF and SF+SG treatments. These results indicate that the application of soil surfactant to pots containing an active water repellent soil layer decreased NH_4–N concentrations within the water repellent layer. Loss of NH_4–N was not due to leaching, as negligible amounts of leaching occurred in the study and we did not see movement of this nutrient into the subsoil layer.

Soil NO_3–N was the primary form of inorganic nitrogen in the soil at the conclusion of the study, having approximately 2 to 4 -fold higher values than NH_4–N, depending on soil layer and treatment (Fig. 3). The application of soil surfactant in the field was the primary driver influencing soil NO_3–N levels; greenhouse soil surfactant application did not impact NO_3–N (Table 1). On average, NO_3–N in the NS and SG treatments were 372% higher than in the SF and SF+SG treatments.

Total inorganic nitrogen levels were unaffected by greenhouse treatment (Table 3). This indicates that the significant amount of NH_4–N loss from the SG greenhouse surfactant treatment was not sufficient to affect total plant available nitrogen levels. This is likely because at the time our soils were sampled NH_4–N comprised only a small proportion of the inorganic nitrogen pool compared to the water repellent NS soil (Fig. 4). There were no significant differences in final seedling density between surfactant treatments.

3.2.4 Final seedling density, above- and below-ground biomass

Final seedling density was affected by field and greenhouse soil surfactant treatments, and their interaction, but not by species (Table 3). Surfactant application in either the field (SF), the greenhouse (SG), or both (SF+SG) allowed 31-34 fold greater seedling density compared to the water repellent NS treatment (Fig. 4). There were no significant differences in final seedling density between surfactant treatments.

Total above- and belowground biomass were influenced by field and greenhouse soil treatments and their interactions, but species response was similar (Table 3). Application of a surfactant (SF, SG, SF+SG) resulted in a 16 to18 and 31 to 55 -fold increase over the repellent NS soil for above- and belowground biomass, respectfully (Fig. 5a). Aboveground biomass was similar between the surfactant SG, SF, and SF+SG treatments. Belowground biomass, however, was between 76-138% higher in the low nitrogen SF and SF+SG treatments as compared to the high nitrogen SG treatment (Fig. 5b).

These results indicate that ameliorating soil water repellency with a surfactant may increase seedling density and biomass. Comparisons between SF and SF+SG treatments, which had similar seedling densities and plant biomasses, indicate there was no phytotoxic effect from the surfactant on the species in this study.

4. Discussion

4.1 Effects of repellency on water response

Previous research has found water repellency to increase soil nitrogen movement by increasing surface runoff (Ravi *et al.,* 2009) and leaching (Lowery *et al*., 2002). However, such research did not examine the effect of water repellency on nitrogen within repellent soils, which experience different moisture conditions than adjacent, wettable soils (Dekker and Ritsema, 2000). Results from our field sampling of water-repellent soils suggest that water repellency can promote the retention of high levels of inorganic nitrogen. While others have speculated on the role of post-fire soil water repellency in preventing such nutrient loss (Boerner, 1982), to our knowledge, we are the first to give experimental data supporting this hypothesis.

Our greenhouse study found water repellency to prevent wetting of water-repellent soil. Applied water ran off, which resulted in lower soil water contents in repellent soils compared to wettable soils. These results are consistent with the findings of Madsen *et al*. 2012. Other studies have also found the presence of water repellency to increase surface runoff (Robichaud, 2000; Madsen *et al*. 2012; Williams *et al*., 2013) and consequently decrease soil water contents (Williams *et al*., 2013). Addition of a surfactant decreased runoff through increased infiltration rates, which nearly doubled soil water contents compared to the soil with no surfactant applied. Our greenhouse trial did not detect a significant loss of soil water via leaching for any treatment. Because infiltration rate is affected by water application rate (Smith *et al*., 1990), slope (Kim and Miller, 1996), soil texture (Moldenhauer and Long, 1964), and water repellency severity (Wallis *et al.,* 1990), variations in these factors may result in greater or lower levels of runoff and leaching.

4.2 Effects of water response on nutrient dynamics

By decreasing soil water content, water repellency may limit microbial nitrogen cycling. Low soil water content limits diffusion of necessary solutes to microbial cells (Papendick and Campbell, 1981; Stark and Firestone, 1995), which limits the ability of microbes to cycle nutrients (Harris, 1981). Low soil water content also decreases intracellular water potentials, which dehydrates and inactivates microbial enzymes (Csonka, 1989). Soil water potential determines which of these factors is most limiting (Stark and Firestone, 1995), but both decrease microbial activity. Increasing soil water content by applying a surfactant to overcome water repellency may increase microbe-driven nitrogen cycling by reversing these effects. Nitrogen cycling processes facilitated by microbes, and therefore affected by soil water contents, include nitrification, microbial immobilization, mineralization, and denitrification.

Similar to microbial nitrogen cycling, low soil water contents in repellent soils may also affect plant nitrogen uptake. When the low soil water contents of repellent soils inhibit plant establishment, as was observed in our greenhouse study, plant nitrogen uptake is likewise inhibited simply because of the absence of plants to assimilate the nitrogen. Even upon establishment in repellent soils, lowered soil water contents may limit plant growth and biomass accumulation, and thereby decrease plant demand for nitrogen (Jamieson *et al*., 2009). When plants are able to establish in hydrophilic patches, access to nitrogen within adjacent repellent soils may still be limited. Plant nitrogen uptake decreases as soil water content decreases (Wang *et al*., 2009). Because nutrients are generally located in the upper soil layers (Jobbágy and Jackson, 2001; Hooker *et al*., 2008), factors that limit soil water content may play additional roles in limiting nitrogen acquisition (Ryel *et al*. 2008; Ryel *et al*. 2010). Located in the upper soil layers, water repellency, by creating low water potentials, may decrease nitrogen diffusion and mass flow to roots (Nye and Tinker, 1977; Hansen and Abrahamsen, 2009; Wu *et al.,* 2009), and nitrogen uptake (BassiriRad and Caldwell, 1992; Jamieson *et al*., 2009), thus limiting nitrogen availability in these soils.

We propose that water repellency prevents the biological use and cycling of nitrogen by limiting soil moisture availability to microbes and plants. In contrast, water-repellent soils treated with surfactant have increased biological nitrogen activity as they accept and retain water. Our greenhouse trial, like our field sampling, indicates some support of this assertion. In the greenhouse, the application of soil surfactant to pots with an active water repellent soil layer doubled soil water contents, and decreased the amount of NH_4–N in the water repellent layer by half. NH_4–N may have been lost from the water repellent layer through nitrification (Maag and Vinther, 1996; Dijkstra *et al.,* 2012), plant uptake (Barber, 1995; Dijkstra *et al.,*2012) and/or microbial immobilization (Bhardwaj and Novák, 1978; Dijkstra *et al.,*2012), all of which increase under moist conditions. Some differences in NH_4–N loss may have also occurred through volatilization, as soil water content has also been shown to affect the rate of this process (Bouwmeester *et al*., 1985; Haynes and Sherlock,1986; McGarry *et al.,* 1987; Liu *et al*., 2007). These results, however, should be interpreted with caution because, relative to the total amount of inorganic nitrogen in the soil, the differences in NH_4–N between surfactant treated and untreated soil were minimal. This negligible difference may be attributed to the short duration of this greenhouse study. Long-term studies may reveal greater changes to inorganic nitrogen availability. This greenhouse study therefore provides justification for additional long-term field research with frequent sampling intervals to better understand how post-fire water repellency controls inorganic nitrogen accessibility.

While our greenhouse study does not indicate that leaching had a large effect on inorganic nitrogen levels, some of the differences in soil nitrogen in the field and greenhouse observations may have been caused by differences in leaching patterns. Under cultivated settings, water repellency promotes leaching through the formation of preferential flow pathways (Blackwell, 2000; Dekker and Ritsema, 2000; Larsbo *et al*., 2008, Aamlid *et al*., 2009). Such leaching occurs as water bypasses repellent soil and flows to hydrophilic patches (Dekker and Ritsema, 2000). Topically- applied fertilizers, fungicides, and other water-translocated chemicals will follow these same pathways as water transports them through the soil profile (Blackwell, 2000). Under such conditions, the application of a surfactant reduces leaching by ameliorating hydrophobic soil, which reduces preferential flow and creates a more homogenous soil moisture distribution (Blackwell, 2000; Larsbo *et al*., 2008). In contrast to cultivated conditions, nutrients in rangeland soils, and those in this study, are already distributed throughout the soil profile. Isolated from water movement by repellent compounds, nutrients in repellent soils may remain unleached from the soil profile. This hypothesis is supported by another study, in which the application of an artificial, water repellent mulch prevented the leaching of a pre-applied fertilizer (Snyder *et al*., 1974).

Our greenhouse study indicates some support of the above hypothesis. While our analysis of all the pots in the study, including those without any leachate, did not show any significant differences in inorganic nitrogen between treatments, we did find supporting trends in samples that had more than 20 ml cumulative leaching. Although the repellent, high nitrogen NS treatment had more than twice the amount of leachate of the wettable, high nitrogen SG treatment, the SG treatment experienced more than twice the NO_3–N leachate loss. This indicates that, under rangeland conditions, the preferential flow leaching patterns experienced by repellent soils may not allow as much soil nitrogen movement as the more uniform soil water content distribution of surfactant-treated, wettable soils.

Because water repellency generally dissipates slowly over several years (Doer *et al.,* 2000; Pierson *et al*. 2001), the use of a surfactant to ameliorate repellency may not fully represent what happens under rangeland conditions. Under a punctuated, surfactant-mediated amelioration of water repellency, the repellency is overcome instantaneously, making the large inorganic nitrogen pool available all at once. In contrast, as water repellency dissipates gradually in the field, nitrogen may likewise decrease at a correspondingly slow rate, releasing the inorganic nitrogen into the system at lower levels over time. However, another possible hypothesis for what happen in unaltered rangeland conditions is the repellent layer may remain severe for a time, but may be rapidly overcome in a particularly wet year (Crockford *et al*., 2006), then making both high water content and high nutrients available to resource-exploiting invasive species. Future studies are needed to investigate the release of nitrogen from naturally dissipating repellent soils over time.

4.3 Effects of water and nutrient responses on seedling response

The effects of water repellency on soil water content and nitrogen retention were hypothesized to affect seedling establishment. In this study, repellent soils (NS) resulted in low seedling density whereas surfactant-treated, ameliorated soils (SG, SF, SF+SG) permitted high seedling density, a finding well supported in the literature (Osborn *et al*., 1967; Krammes and Osborn, 1969; Debano and Conrad, 1974; Madsen *et. al.,* 2012). In a similar trend to seedling density, plant biomass was high in surfactant-treated soils and low in repellent soils. This difference in seedling growth between repellent and surfactant-treated soils resulted mainly from differences in soil water content, and therefore soil water potential and plant available water. Repellent soils experienced low soil water contents, whereas the surfactant treatments, by overcoming repellency, allowed for a nearly doubled increase in soil water content.

High nitrogen, wettable soils (SG) were expected to produce more plant biomass than wettable, low nitrogen soils (SF, SF+SG). While no treatment effect for aboveground biomass was detected among surfactant-treated soils, belowground biomass increased under lower nitrogen conditions. This may indicate a response by the seedlings to increase their nitrogen-uptake capacity and thus compensate for low nitrogen conditions, as has been observed in other research (Boot and Mensink, 1990).

Nutrient availability influences site susceptibility to invasion (Paschke *et al*., 2000). Some have suggested that increases in available soil nitrogen following wildfire (Covington *et al*., 1991) may benefit cheatgrass more than many native perennial species (Blank *et al.,* 2007; Esque *et al*., 2010). High nutrient, wettable soils (SG) were therefore expected to benefit the annual nitrophilic weed, *B. tectorum* more than the perennial *P. spicata*. However, no species differences were detected in this study. The figures in the appendix show the plant response variables separated by species, in addition to plant total nitrogen concentration. Previous research indicates that, at the seedling stage, annual and perennial grasses experience proportionally similar reductions in relative growth rates under lowered nitrogen conditions (James, 2008) and the competitive interactions remain unchanged (James *et al*., 2011) relative to high nitrogen conditions. These observations may explain the lack of significant differences between the species in this study.

5. Conclusions

Factors that affect soil-water relations can strongly influence ecosystem recovery following catastrophic disturbances, such as fire. This study suggests that post-fire soil water repellency is one such factor. By decreasing soil water contents, water repellency may both promote the retention of inorganic nitrogen and limit seed germination and seedling survival. While this study hypothesized that increased nitrogen retention in repellent soils would play a major role in seedling establishment, such influences were minimal compared to the impact of repellency on water availability. This research further indicates that, by overcoming soil water repellency and increasing soil water contents, surfactants may be a useful management tool to promote the recovery of perennial grasses.

Inferences of this study are limited because research was performed at only one site; additional field research is merited to continue to understand the interactive effects of water repellency and nutrient islands on plant successional processes. While we hypothesized that high inorganic nitrogen levels in newly ameliorated repellent soils would facilitate nitrophilic weed establishment, this study found no difference in the response between the invasive annual and native perennial grass species. The time limitations of a greenhouse study reduce the ability to observe long-term effects of water repellency and soil nitrogen on seedling succession. Longer studies would be able to evaluate the competitive effects of mature perennial grass traits, which may give these species advantages over annuals. The short-term greenhouse observations of this study therefore merit additional research under a long duration field study to determine whether water repellency may increase the success of invasive weeds by maintaining high soil nutrients until repellency dissipation makes the nutrients accessible to the invasive weeds within islands of fertility.

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TABLES

Table 1. Matrix of soil treatments and characteristics, which include: field soil treatment, greenhouse soil treatment, inorganic soil nitrogen levels, soil water repellency severity and soil water content (SWC) levels at the start of the greenhouse trial.

Label*	Field treatment	Greenhouse treatment	Nitrogen levels	Repellency severity	SWC
NS	Water	Water	High	Severe	Low
SG	Water	Surfactant	High	None	High
SF	Surfactant	Water	Low	None	High
SF+SG	Surfactant	Surfactant	Low	None	High

* Soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG).

Table 2. Mixed ANOVA results for the effects of soil layer and treatment on soil NH_4–N and soil NO_3–N three years following field treatment, but prior to the greenhouse trial.

	Soil NH_4–N		Soil NO_3–N	
	F	*P*	*F*	*P*
Soil layer	8.86	**0.0013**	10.67	**0.0007***
Soil treatment	2.67	0.1155	23.98	**<0.0001**
Layer × Treatment	0.84	0.4435	12.67	**0.0003**

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

Table 3. Results of mixed ANOVA models at the end of the greenhouse trial for total runoff, total leachate, soil water content (SWC), soil NH_4–N, soil NO_3–N, total inorganic nitrogen, final seedling density, and above and below-ground biomass, by treatment, species, soil layer (NH_4–N, NO_3–N, and total inorganic nitrogen only), and their interactions.

	Runoff		Leachate*		SWC	
	F	*P*	*F*	*P*	*F*	*P*
Field soil treatment (F.) †	17.07	**0.0002**‡	0.91	0.3521	0.82	0.3780
Greenhouse soil treatment (G.) †	33.61	**<0.0001**	0.01	0.9117	13.10	**0.0023**
Species	0.76	0.3900	—	—	2.18	0.1596
F. × G.	22.09	**<0.0001**	2.20	0.1534	7.69	**0.0136**
F. × Species	1.88	0.1790	—	—	0.00	0.9877
G. ×Species	0.70	0.4099	—	—	0.77	0.3931

	Soil NH_4–N		Soil NO_3–N		Inorganic N	
	F	*P*	*F*	*P*	*F*	*P*
Field soil treatment (F.)	450.81	**<0.0001**	92.85	**<0.0001**	272.90	**<0.0001**
Greenhouse soil treatment (G.)	9.15	**0.0029**	0.14	0.7049	0.04	0.8377
Species	0.42	0.5179	1.39	0.2403	0.68	0.4111
F. × G.	30.44	**<0.0001**	2.51	0.1157	17.59	**<0.0001**
F. × Species	0.97	0.3266	0.49	0.4861	0.92	0.3398
G. × Species	5.56	**0.0196**	0.21	0.6448	1.55	0.2153
Soil layer	15.61	**<0.0001**	5.43	**0.0054**	0.25	0.7816
F. × Soil layer	4.36	**0.0145**	2.65	0.0742	3.19	**0.0444**
G. × Soil layer	4.40	**0.0140**	0.37	0.6890	1.21	0.3005
Species × Soil layer	0.11	0.8998	2.41	0.0940	1.60	0.2049

	Final seedling density		Above-ground biomass		Below-ground biomass	
	F	*P*	*F*	*P*	*F*	*P*
Field soil treatment (F.)	140.21	**<0.0001**	48.35	**<0.0001**	121.32	**<0.0001**
Greenhouse soil treatment (G.)	124.65	**<0.0001**	45.04	**<0.0001**	21.15	**<0.0001**
Species	3.49	0.0679	2.63	0.1115	0.20	0.6551
F. × G.	125.88	**<0.0001**	41.61	**<0.0001**	42.77	**<0.0001**
F. × Species	1.75	0.1926	4.00	0.0511	0.76	0.3871
G. × Species	0.90	0.3485	2.72	0.1058	1.12	0.2957

* Due to low leachate levels, data was combined by species prior to analysis.

† "Field soil treatment" and "Greenhouse soil treatment" refer to two consecutive factorial treatment levels performed on the same soil, i.e. first, treatment with surfactant or water in the *field* and second, treatment with surfactant or water in the *greenhouse*. These two treatment levels combine to create four final soil treatments, which were then evaluated in the greenhouse trial.

‡ Significant factors ($P < 0.05$) are highlighted in bold.

Table 4. Mean values and Tukey HSD pairwise comparisons for total runoff, total leachate and soil water content (SWC) by treatment.

Soil treatment*	Total runoff (ml)		Total leachate (ml)		SWC (m^3/m^3)	
NS	824.2	a†	41.2	a	0.05	a
SG	127.6	b	11.8	a	0.1	b
SF	238.2	b	5.4	a	0.08	b
SF+SG	165.3	b	22.7	a	0.09	b

* Soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG).

† Means with different letters are significantly different from each other ($P < 0.05$).

Table 5. Results of mixed ANOVA for the amount of NO_3–N lost through runoff and leachate, by soil treatments, species, and their interactions.

	Runoff		Leachate	
	F	*P*	*F*	*P*
Field soil treatment (F.)*	13.27	**0.0008†**	0.08	0.7748
Greenhouse soil treatment (G.)*	8.64	**0.0054**	0.58	0.4509
Species	1.51	0.2260	0.00	0.9623
F. × G.	6.01	**0.0187**	0.20	0.6598
F. × Species	0.48	0.4935	2.06	0.1604
G. × Species	0.07	0.7918	0.61	0.4407

* "Field soil treatment" and "Greenhouse soil treatment" refer to two consecutive factorial treatment levels performed on the same soil, i.e. first, treatment with surfactant or water in the *field* and second, treatment with surfactant or water in the *greenhouse*. These two treatment levels combine to create four final soil treatments, which were then evaluated in the greenhouse trial.

† Significant factors ($P < 0.05$) are highlighted in bold.

FIGURES

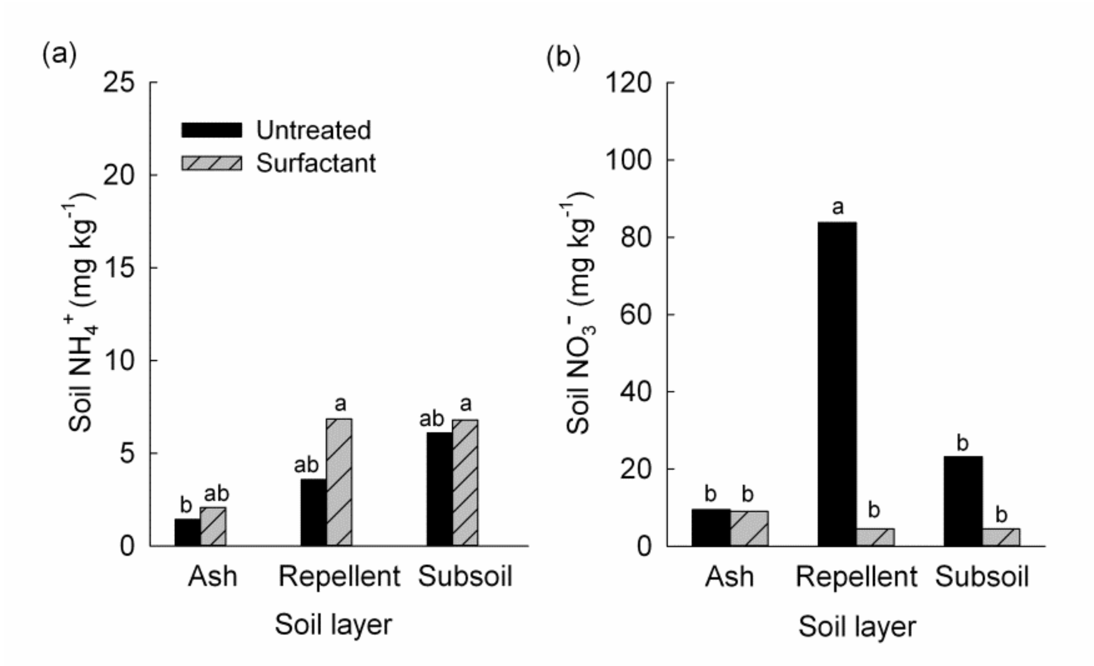

Figure 1. (a) Soil NH_4–N and (b) NO_3–N levels prior to the initiation of the greenhouse treatment. Samples were taken from three soil layers within untreated and surfactant treated field soils. Soil layers include: the top ash layer (Ash); the repellent zone (Repellent); and the soil below the repellent zone (Subsoil). Values are means, with unique letters indicating significant differences between soil layers by treatment ($P < 0.05$).

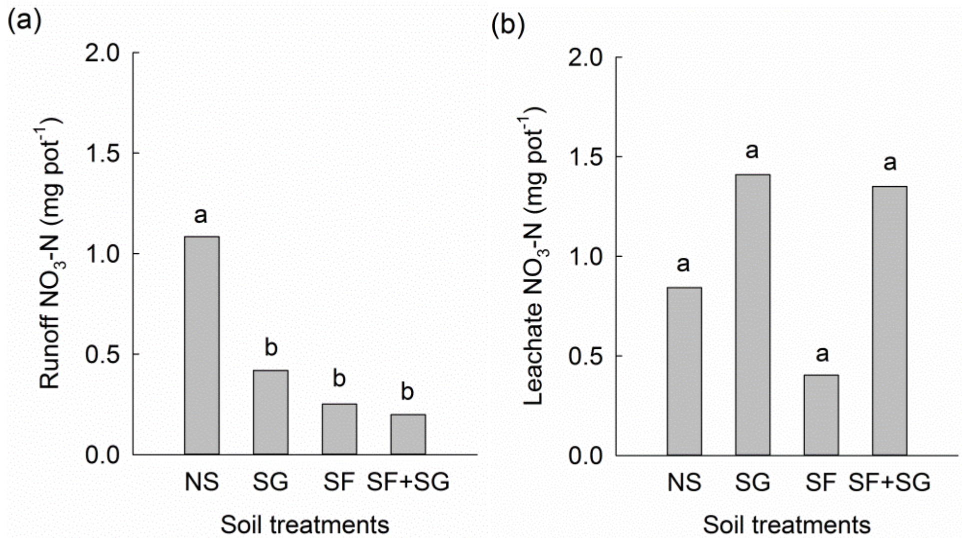

Figure 2. Amount of NO_3–N lost per pot through (a) runoff and (b) leachate over the duration of the study. NO_3–N levels found in the irrigation water were 0.87 ± 0.04 (SE) mg L^{-1} NO_3–N. Soil treatments include: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Values are means, with unique letters indicating significant differences between soil layers by treatment ($P < 0.05$).

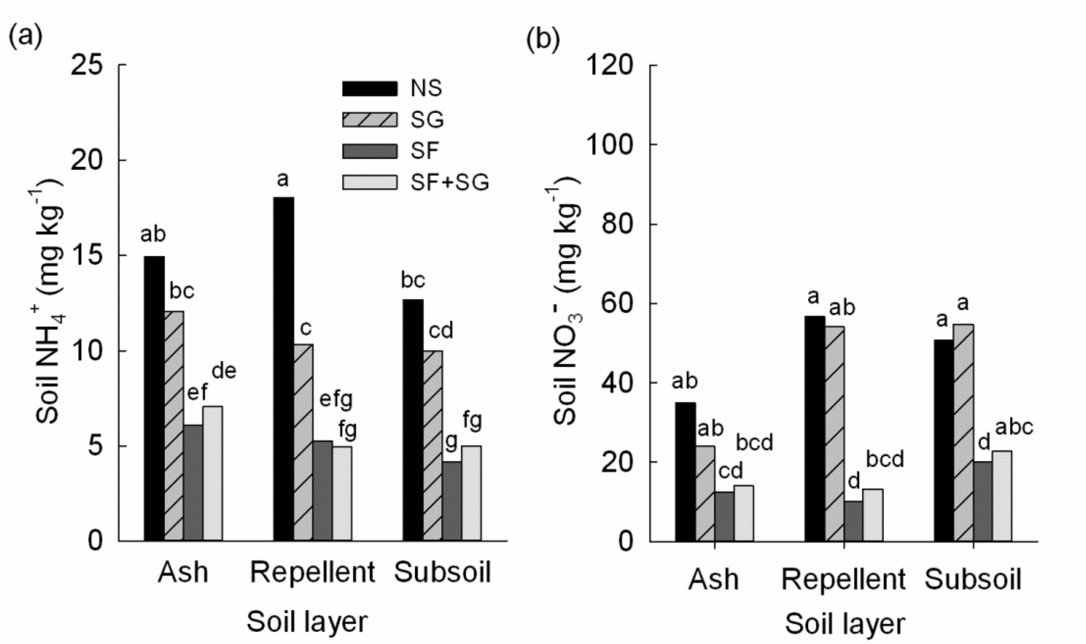

Figure 3. (a) Soil NH_4–N and (b) NO_3–N levels at the end of the greenhouse trial, combined by species for each soil treatment by soil layer. Soil treatments include: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Samples were taken from three soil layers, which include: the top ash layer (Ash); the repellent zone (Repellent); and the soil below the repellent zone (Subsoil). Values are means, with unique letters indicating significant differences between soil layers by treatment ($P < 0.05$).

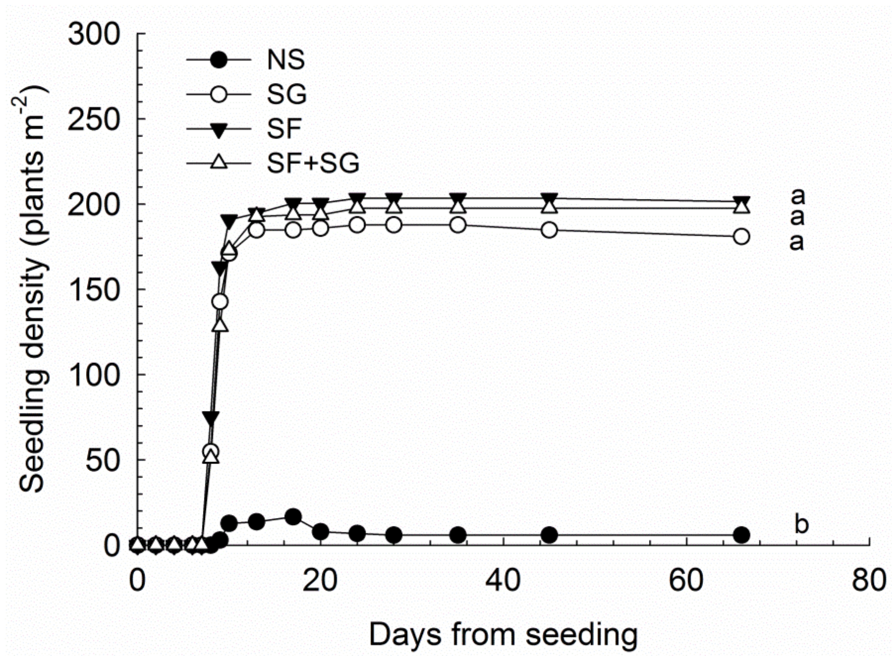

Figure 4. Seedling density, combined for both tested species (*Pseudoroegneria spicata* and *Bromus tectorum*), within each of the four soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Values are means with unique letters indicating significance differences between treatments ($P < 0.05$).

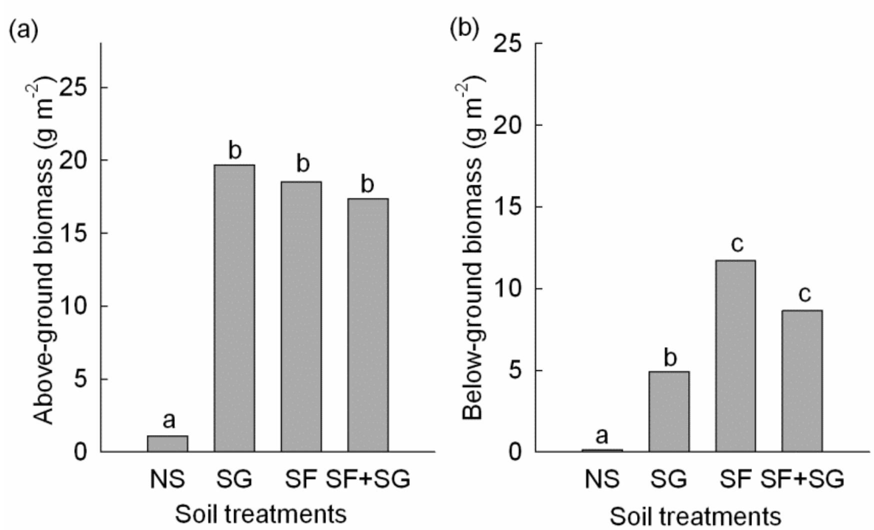

Figure 5. (a) Above-ground biomass and (b) below-ground biomass, combined for both tested species (*Pseudoroegneria spicata* and *Bromus tectorum)* within each of the four soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Measurements were taken at the end of the greenhouse trial and are shown as means, with unique letters indicating significant differences between treatments ($P < 0.05$).

APPENDIX

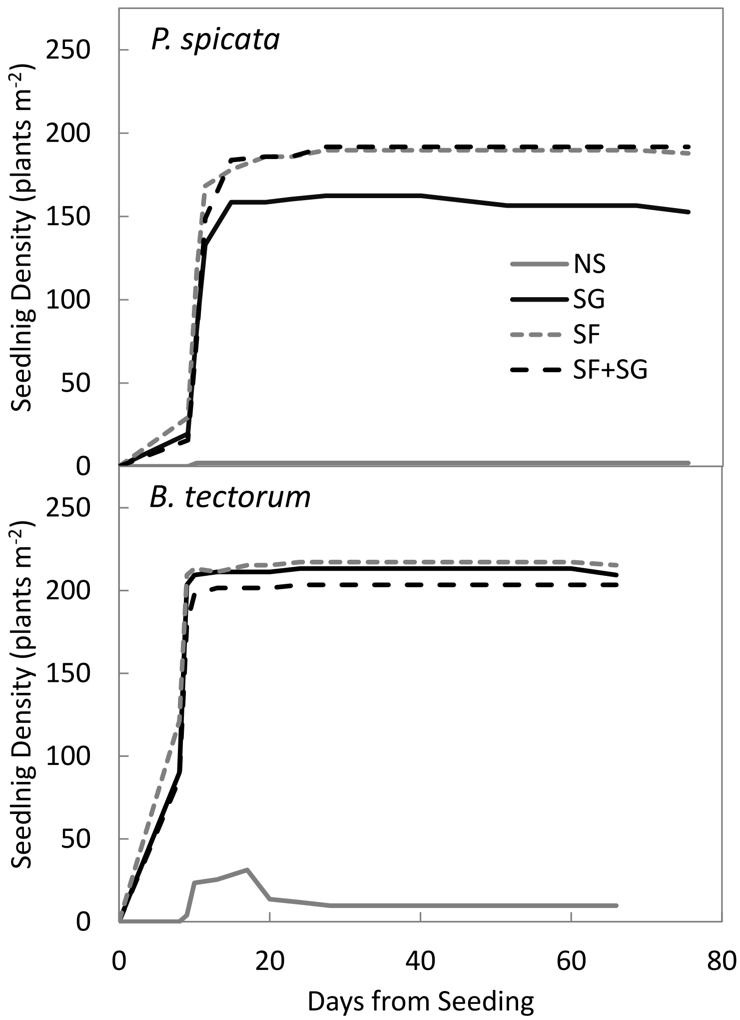

Figure 1. Mean seedling density for both tested species (*Pseudoroegneria spicata* and *Bromus tectorum*), within each of the four soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG).

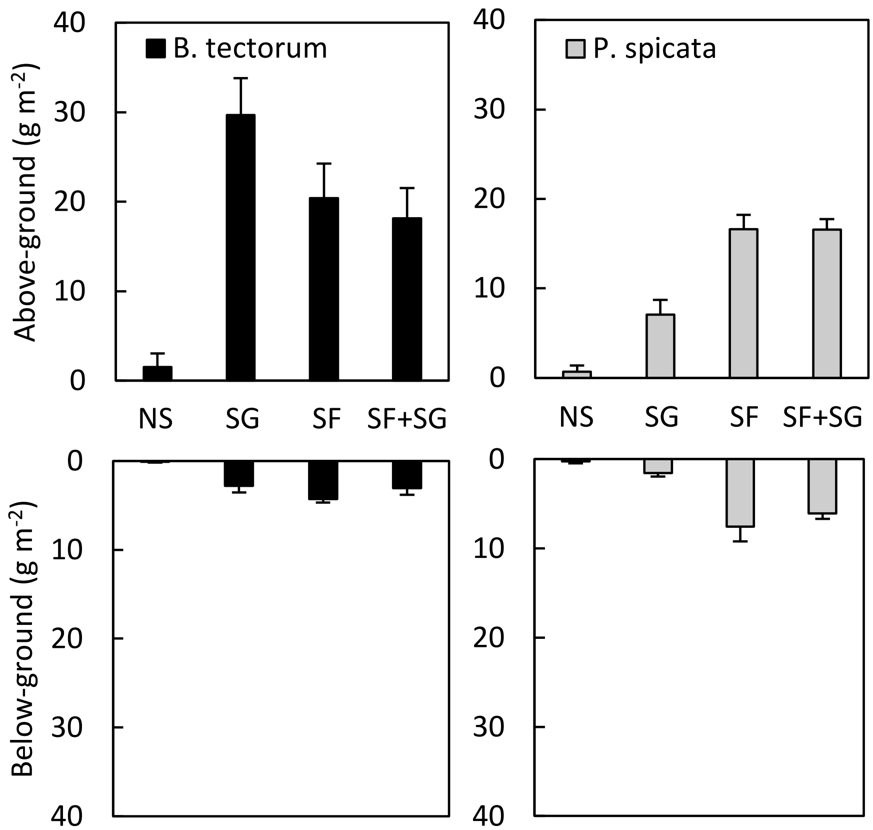

Figure 2. (a) Above-ground biomass and (b) below-ground biomass for both tested species (*Pseudoroegneria spicata* and *Bromus tectorum)* within each of the four soil treatments: No surfactant (NS); greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Measurements were taken at the end of the greenhouse trial and are means (±1 SE).

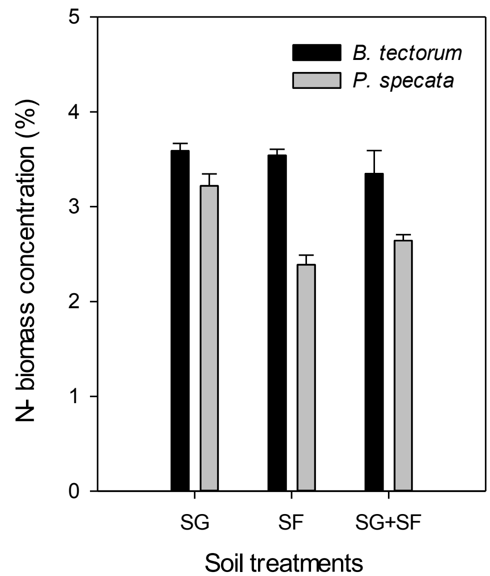

Figure 3. Total nitrogen biomass concentration for *Bromus tectorum* and *Pseudoroegneria spicata* at time of harvest for all soil treatments except the no surfactant (NS) soil treatment, which only had one surviving replicate for each species. Soil treatments include: greenhouse surfactant treatment (SG); field surfactant treatment (SF); and field and greenhouse surfactant treatment (SF+SG). Measurements are means (±1 SE).