Soil Surfactant Products for Improving Hydrologic Function in Post-Fire Water-Repellent Soil

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There is a wide range of soil surfactant chemistries on the market today that are primarily designed for the treatment of water-repellent soils in cropping and turfgrass systems. These chemicals may also have potential in treating the deleterious effects associated with post-fire water-repellent soils. The objective of this study was to compare 13 commercially available soil surfactant products with regard to their ability to influence water penetration and soil water-holding capacity in post-fire water-repellent soil. The impact of the surfactant on soil water penetration and water-holding capacity was determined through water drop penetration time tests and laboratory column infiltration experiments, respectively. All products evaluated in the study improved water penetration and generally increased soil water retention; however, the degree of performance varied widely among products. Irrigaid Gold, Advantage, Penn Wetting, Pervaide, and Tournament Ready were typically the most effective at treating soil water repellency. Hydro Wet, Intake, Attain FC, Wet-Sol Gro, and EZ Wet in general showed an intermediate response, while Fulmax, PenaTron, and Penex were less effective than the other products. We assume that the products that had the greatest improvements in water penetration and retention will also be the most effective in restoring hydrologic function of post-fire water-repellent soils; however, the full utility of the products was not demonstrated in this study, particularly with respect to plant growth. Additional laboratory and field studies are merited for understanding how these different surfactant chemistries influence revegetation success.

Abbreviations: a.s.i., active surfactant ingredient; LDPT, liquid drop penetration time; VWC, volumetric water content.

Soil water repellency (or hydrophobicity) occurs when complex organic acids that exhibit hydrophobic properties coat soil particles (Doerr et al., 2000; Franco et al., 2000). These wax-like substances are ubiquitous in vegetated soils, having been derived from microorganisms (Bond and Harris, 1964; Chan, 1992), plant materials (DeBano et al., 1970; McGhie and Posner, 1981), and litter (McGhie and Posner, 1980). In general, high-severity fires can induce or intensify soil water repellency as the hydrophobic substances in the soil and litter are volatilized, pyrolyzed, and redistributed deeper into the soil profile (DeBano et al., 1970; Savage, 1974; Doerr et al., 2000).

In the first few years following fire, soil water repellency can substantially reduce water infiltration into the soil, promote overland flow, and accelerate soil erosion (Cerdá and Robichaud, 2009; Krammes and DeBano, 1965; Shakesby and Doerr, 2006). These direct effects of soil water repellency can limit soil moisture near the soil surface (Dekker and Ritsema, 1994), which increases wind erosion

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Soil Sci. Soc. Am. J. 77:1825–1830
doi:10.2136/sssaj2012.0305

Received 17 Sept. 2012.
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(Ravi et al., 2010) and reduces moisture availability for plant reestablishment from seed (Osborn et al., 1967; DeBano et al., 1970; Savage, 1974; Madsen et al., 2012).

Soil surfactants (or wetting agents) have been utilized to counteract the deleterious effects of soil water repellency (DeBano, 2000). The mode of action varies among commercial products, but in general, surfactants are composed of organic molecules with hydrophobic tails and hydrophilic heads. This chemical composition lowers the surface tension of the water, thus increasing infiltration. Furthermore, surfactants render the soil wettable as the hydrophobic tail of the wetting agent chemically bonds to the hydrophobic coating on the soil particle, while the hydrophilic head attracts water molecules, allowing them to pass into the soil (Cisar et al., 2000; Kostka, 2000).

Early post-wildfire soil surfactant research began in the 1960s (Osborn et al., 1967; Krammes and Osborn, 1969; DeBano and Conrad, 1974; DeBano, 2003). These small-plot evaluations demonstrated the efficacy of soil surfactants for reducing post-fire erosion. Although the use of soil surfactants as a post-fire water-repellency treatment has been minimal since that time (Dekker et al., 2005; Robichaud et al., 2000), interest in soil surfactants has remained high for urban landscape management (Kostka, 2000; Karnok and Tucker, 2001; Oostindie et al., 2008, 2011), horticulture (Urrestarazu et al., 2008), and agricultural soils (Lowery et al., 2004; Hopkins and Cook, 2007). Consequently, there have been significant advancements in soil surfactant formulations that have increased the effectiveness of these chemicals in improving soil hydrologic behavior (Cisar et al., 2000; Kostka and Bially, 2005; Moore et al., 2010). Such achievements provide merit for further testing of soil surfactants in post-fire wildland soils.

A wide range of surfactant chemistries have been designed for the management of water-repellent soil. These chemical formulations include anionic surfactants, nonionic surfactants, fulvic acids, and nonionic block copolymers (Moore et al., 2010). While there has been some small-scale testing of these surfactant products in post-fire soils (Darboux et al., 2008; Madsen et al., 2012), comprehensive, head-to-head comparison studies are lacking. The objective of this study was to evaluate various commercially available soil surfactant products to determine which was most adept at improving water penetration and soil water retention in post-fire water-repellent soils.

MATERIALS AND METHODS

Soil Collection

Water-repellent soil was obtained approximately 13.7 km northwest of Milford, UT (38°26′12″ N, 112°51′46″ W, elevation 1847 m) within the boundaries of the 2007 Milford Flat wildfire. The soil has been classified as a coarse sandy loam, mixed, mesic Aridic Haploxeroll (Soil Survey Staff, 2009). Madsen et al. (2011) showed that the soil in the area exhibited a wettable layer of primarily burned litter material down to 1.4 ± 0.12 cm (average ± standard error; *n* = 35). The soil below this layer was primarily mineral soil and was water repellent down to 6.1 ± 0.53 cm below the soil surface. Soil was collected from underneath burned Utah juniper trees [*Juniperus osteosperma* (Torr.) Little] from this region in June 2008 (11 mo after the fire). Because the soil was not uniformly water repellent, we sprayed a 1-m^2 area with roughly 8 to 10 L of water using a pressurized mist sprayer. This allowed us to identify and collect water-repellent soil and exclude wettable soil because the water-repellent soil remained dry after spraying. In the laboratory, the soil was air dried for 48 h, sieved (10 mm), and thoroughly mixed. Textural analysis showed that the soil contained 63% sand, 10% silt, and 27% clay (measured by the hydrometer method; Day, 1965). The organic matter content was 5.6% (measured by dichromate oxidation; Walkley and Black, 1934).

Surfactant Testing

Thirteen soil surfactant products (Table 1) were evaluated in the laboratory (∼23°C and 47–68% relative humidity) against an untreated control for their ability to improve soil water penetration and retention. Water penetration and retention were assessed with a liquid drop penetration time (LDPT) test, similar to that described by Ritsema et al. (2008), and infiltration column tests, respectively. In both tests, products were applied to air-dry, water-repellent soil at concentrations of 6 and 12 mL of active surfactant ingredient (a.s.i.) L^{-1}. Solutions were prepared using tap water that had an electrical conductivity of 0.2 dS m^{-1}, with $CaCO_3$ and $MgCO_3$ the dominant salts.

Table 1. Surfactant products evaluated in a comparative study with their active ingredients and manufacturer. Each surfactant evaluated in the study was assigned an acronym based off its active ingredient.

Trade name	Active ingredients	Acronym	Manufacturer
Advantage	ammonium alkyl ether sulfate; alkyl aryl polyethoxylates	AES/AAP	Wilbur-Ellis Co.
Attain FC	ammonium laureth sulfate	ALS-1	J.R. Simplot Co.
EZ Wet	nonylphenolpolyethoxylate, oleic acid	NOA	Grow More Inc.
Fulmax	fulvic acid	FA	JH Biotech Inc.
Hydro Wet	poloxanlene, 2-butoxyethanol	P2B	Kalo Inc.
Intake	ammonium laureth Sulfate	ALS-2	Ag Concepts Corp.
Irrigaid Gold	alkoxylated polyols; Glucoethers	APG	Aquatrols Corp.
PenaTron	spirostant; sarsaponin	SS	Maz-Zee S.A.
Penex	ammonium laureth sulfate	ALS-3	JH Biotech Inc.
Penn Wetting	polyoxyethylene-polyoxypropylene siloxane	PPS	RSA Microtech
Pervaide	ethoxylated alkylphenol	EAP	Ag Concepts Corp.
Tournament Ready	nonionic carbohydrate surfactants, polyoxythylenepolyoxyethylene-polyoxypropylene glycol, polydimethylsiloxane	PPGP	Kalo Inc.
Wet-Sol Gro	alkyl phenyl-hydroxypoly oxyethylene; polydimethylsiloxane	APOP	Schaeffer Mfg. Co.

For LDPT testing, a randomized complete block design (by order of tests performed) with five replications per treatment was implemented. The LDPT tests were performed by pipetting a 0.17-mL drop of untreated or surfactant-treated water on the soil surface and recording the time for the water drop to break surface tension and penetrate into the soil.

Infiltration column tests were conducted within a randomized complete block design with four replicates per treatment. Soil (120 g) was packed in clear, 40-mm-diameter polyvinyl chloride columns, to a depth of 60 mm, which produced a core volume of 75.4 cm^3 with a bulk density of 1.59 g cm^{-3}. The bottom of the column was covered with cheesecloth and attached to the column with a zip tie. Filled soil columns were clamped and suspended above the laboratory bench. Soil water retention was measured by pouring 45 mL of surfactant solution, or water in the case of the control, directly onto the soil surface of each column. This volume of liquid added produced an initial hydraulic head of 29 mm above the soil surface and was equal to the amount required to bring the soil to field capacity (59.7% volumetric water content [VWC]), with field capacity determined by the "container capacity" method on five replicate columns (Cassel and Nielsen, 1986). Soils columns were left on the stand to drain for 24 h after treatment. The VWC was determined by subtracting the weight of the soil column 24 h after treatment from the pretreatment weight and dividing by the volume of soil. All treated soil columns were left suspended in the laboratory for 31 d after treatment. During this period, the added soil water evaporated, and the columns of soil returned to pretreatment weight. Soil water retention was again measured with tap water using the methods described above.

Statistical Analysis and Data Reporting

Water drop penetration and water retention data were analyzed with a split-plot design using a mixed-model ANOVA using the SAS PROC MIXED model (Version 9.1, SAS Institute). Surfactant type was the main-plot factor and surfactant concentration was the split-plot factor in the model. For water retention, treatment period was added as a sub-subplot factor. When significant main or interactive effects were found, mean values were separated using the LSMEANS procedure. Before analysis, normality and homogeneity were tested using the Shapiro–Wilk test and Levene's test, respectively, in PROC UNIVARIATE. The LDPT data were logarithmically transformed to reduce problems with deviance from normality. For all comparisons, a significance level of $P < 0.05$ was used. Means of untransformed data are reported with standard errors (mean ± SE).

RESULTS

Water Drop Penetration Time

The LDPT was influenced by surfactant type and concentration as well as the interaction between these variables (Table 2). All surfactant products decreased the LDPT compared with the control at both 6 and 12 mL a.s.i. L^{-1} (Table 3). There was a difference among the products in their ability to increase soil water penetration. At 6 mL a.s.i. L^{-1}, APG, AES/AAP, PPGP, PPS, and EAP had similar values and produced quicker LDPTs than the other products. The average LDPT of this group was more than approximately four orders of magnitude more rapid (3328-fold) than the control. The next distinct group of surfactant products included ALS-2, P2B, ALS-1, and NOA. On average, this group had LDPTs that were approximately three orders of magnitude more rapid (1288-fold) than the control. The remaining surfactant products all had statistically different LDPT values in comparison to each other. The LDPTs of APOP, ALS-3, SS, and FA were 609-, 126-, 23-, and 1.7-fold, respectively, faster than the control.

Table 2. Degrees of freedom (df), F, and P (Pr > *F*) values from mixed-model ANOVA for the effects of water drop penetration time (LDPT) and water retention. Values in bold are statistically significant (*P* < 0.05).

		LDPT		Water retention	
Effect	df	*F*	*P* > *F*	*F*	*P* > *F*
Product (P)	13	1069.7	**<0.001**	199.7	**<0.001**
Concentration (C)	1	150.4	**<0.001**	261.9	**<0.001**
Time (T)	1	–	–	0.2	0.699
P × C	13	6.8	**<0.001**	7.9	**<0.001**
C × T	1	–	–	3.4	0.068
P × T	13	–	–	175.4	**<0.001**
P × C × T	13	–	–	16.5	**<0.001**

Increasing the surfactant concentration to 12 mL a.s.i. L^{-1} decreased the LDPT for all products except ALS-2 (Table 3). At 12 mL a.s.i. L^{-1}, the LDPT of the surfactants generally fell within the same statistically similar groups as they did at 6 mL L^{-1} a.s.i. (Table 3). On average, surfactant products that produced the quickest LDPTs (APG, AES/AAP, PPGP, PPS, and EAP) were 6770-fold faster than the control at 12 mL of a.s.i. L^{-1}. Unlike at the 6 mL a.s.i. L^{-1} concentration, within this group APG had a significantly faster LDPT than EAP, but this

Table 3. Water drop penetration times for soil surfactants and an untreated control. Products were evaluated against each other at 6 and 12 mL of active surfactant ingredient (a.s.i.) L^{-1} of tap water. The table also shows the difference in water drop penetration time between the surfactant concentrations for each product.

	Water drop penetration time		
Surfactant†	6 ml L^{-1}	12 ml L^{-1}	Difference
		s	
APG	5.4 ± 0.9 h‡	1.6 ± 0.3 i	−3.8
PPGP	5.2 ± 0.9 h	2 ± 0.0 hi	−3.2
AES/AAP	3.8 ± 0.5 h	2 ± 0.0 hi	−1.8
PPS	5.4 ± 0.7 h	2 ± 0.4 hi	−3.4
EAP	4.0 ± 0.0 h	2.8 ± 0.3 h	−1.2
ALS-2	9.0 ± 0.7 g	17.8 ± 1.9 e	8.8
P2B	11.8 ± 1.4 fg	5 ± 0.4 g	−6.8
ALS-1	12.0 ± 0.8fg	5.4 ± 0.3 g	−6.6
NOA	16.4 ± 3.1 ef	6.4 ± 0.7 g	−10.0
APOP	26.0 ± 8.7 e	12.8 ± 2.4 f	−13.2
ALS-3	125.6 ± 53.3 d	29.2 ± 7.3 d	−96.4
SS	702.6 ± 188.8 c	390 ± 101.8 c	−312.6
FA	9113.4 ± 398.7 b	5809 ± 396.7 b	−3304.4
Control	15842.5 ± 850.8 a	14083 ± 517.7 a	−1759.9

† APG, Irrigaid Gold; PPGP, Tournament Ready; AES/AAP, Advantage; PPS, Penn Wetting; EAP, Pervaide; ALS-2, Intake; P2B, Hydro Wet; ALS-1, Attain FC; NOA, EZ Wet; APOP, Wet-Sol Gro; ALS-3, Penex; SS, PenaTron; FA, Fulmax.

‡ Mean ± standard error. Mean times followed by the same letter are not significantly different when comparing surfactants within the 6 or 12 mL a.s.i. L^{-1} concentrations ($P < 0.05$).

Table 4. Water retained in soil columns after applying 45 mL of surfactant solution or an untreated control. Products were initially evaluated against each other at 6 and 12 mL of active surfactant ingredient (a.s.i.) L^{-1} of tap water. Treated soil columns were then air dried for 31 d and the measurements repeated using tap water only in place of a surfactant solution. The table also shows the difference in water retention between surfactant concentrations for each product.

	Water retention							
	Following surfactant treatment (0 d)			Following water application to previously treated soil (31 d)			Difference between 0 and 31 d	
Surfactant†	6 ml L^{-1}	12 ml L^{-1}	Difference	6 ml L^{-1}	12 ml L^{-1}	Difference	6 ml L^{-1}	12 ml L^{-1}
	%							
APG	41.2 ± 1.7 a‡	45.1 ± 1.4 a	3.8	43.9 ± 1.1 ab	46.6 ± 0.4 a	2.7	2.6	1.5
PPGP	41.7 ± 0.7 a	44.2 ± 1.4 a	2.5	42.4 ± 0.7 b	44.6 ± 1.0 ab	2.1	0.7	0.4
AES/AAP	45.6 ± 1.1 a	45.5 ± 1.2 a	−0.1	44.2 ± 2.1 ab	45.7 ± 1.5 a	1.5	−1.4	0.2
PPS	45.8 ± 0.6 a	45.6 ± 1.1 a	−0.2	45.5 ± 0.5 ab	46.2 ± 2.2 a	0.8	−0.3	0.6
EAP	45.2 ± 2.1 a	48.1 ± 0.9 a	2.9	47.8 ± 2.1 a	49.6 ± 0.8a	1.8	2.6	1.5
ALS-2	34.2 ± 2.6 b	46.9 ± 1.2 a	12.7	19.4 ± 2.7 cd	39.2 ± 2.0 b	19.8	−14.8	−7.7
P2B	35.8 ± 1.7 b	45.9 ± 0.5 a	10.2	41.9 ± 0.8 b	46.7 ± 0.9 a	4.8	6.1	0.7
ALS-1	33.7 ± 2.0 b	44.2 ± 1.8 a	10.5	15.6 ± 4.1 d	39.5 ± 4.0 b	23.9	−18.1	−4.7
NOA	18.9 ± 2.1 c	40.4 ± 1.2 a	21.5	21.4 ± 1.7 c	45.2 ± 2.1 a	23.7	2.6	4.8
APOP	14.8 ± 2.5 c	34.9 ± 5.2 b	20.1	17.8 ± 2.8 cd	39.5 ± 5.8 b	21.7	3.0	4.6
ALS-3	9.6 ± 1.4 d	17.7 ± 1.1 c	8.1	10.4 ± 0.8 e	18.4 ± 1.7 c	8.0	0.8	0.7
SS	3.3 ± 0.7 e	6.9 ± 1.1 d	3.7	3.9 ± 1.1 f	10.6 ± 0.8 d	6.7	0.6	3.7
FA	5.9 ± 1.3 d	3.6 ± 1.0 de	−2.4	6.4 ± 2.0 ef	5.2 ± 1.4 e	−1.2	0.4	1.7
Control	1.7 ± 0.2 e	1.5 ± 0.4 e	−0.2	2.3 ± 0.4 f	2.9 ± 0.8 e	0.6	0.6	1.4

† APG, Irrigaid Gold; PPGP, Tournament Ready; AES/AAP, Advantage; PPS, Penn Wetting; EAP, Pervaide; ALS-2, Intake; P2B, Hydro Wet; ALS-1, Attain FC; NOA, EZ Wet; APOP, Wet-Sol Gro; ALS-3, Penex; SS, PenaTron; FA, Fulmax.

‡ Mean ± standard error. Means followed by the same letter are not significantly different when comparing surfactants within the 6- or 12-mL a.s.i. L^{-1} concentrations ($P < 0.05$).

difference was minimal. For the next distinct group of surfactant products (ALS-2, P2B, ALS-1, and NOA), the LDPT of ALS-2 compared with the other products was relatively less at 12 mL a.s.i. L^{-1} than it was at 6 mL a.s.i. L^{-1} (Table 3), which explains the significant interaction shown in Table 2. On average, this group's LDPTs were 1628-fold faster than the control. The remaining surfactant products all had statistically different LDPTs from each other and in the same order as at the 6 mL a.s.i. L^{-1} concentration, with APOP, ALS-3, SS, and FA having 1100-, 482-, 36-, and 2.4-fold faster LDPTs, respectively, than the control.

Infiltration Column Tests

When only water was applied to the soil columns (no surfactant treatment), the liquid primarily moved through preferential flow paths (Oostindie et al., 2008). On average, only 2.9% of the water added was retained in the soil after 24 h (Table 4). Application of a surfactant to the water improved soil water retention, with significant surfactant type, surfactant concentration, and surfactant type × concentration, surfactant type × time period, and surfactant type × concentration × time period interactions (Table 2).

At 6 mL a.s.i. L^{-1}, the surfactant products and the control separated into five distinct soil water retention groups (Table 4). Similar to the LDPT results, PPS, AES/AAP, EAP, PPGP, and APG responded similarly and retained the highest amount of soil water. Unlike the control, where water moved primarily through preferential flow paths, we observed a near-homogeneous wetting of the soil column. On average, water retention in this group was 26-fold higher than the control, with these columns having VWC just below field capacity. The second highest water retention group was P2B, ALS-2, and ALS-1; on average, water retention for these products was 20-fold higher than the control. The average water retention of the NOA- and APOP-treated soils was 10-fold higher than the control; while ALS-3 and FA retained, on average, fivefold more soil water than the control, and SS was not different from the control for water retained after treatment.

The surfactants that retained the most water at 6 mL a.s.i. L^{-1} did not show major increases in soil water retention at 12 mL a.s.i. L^{-1}, which indicates that the effectiveness of these products had plateaued at the 6 mL a.s.i. L^{-1} concentration (Table 4). At 12 mL a.s.i. L^{-1}, EAP, ALS-2, P2B, PPS, AES/AAP, APG, ALS-1, PPGP, and NOA had similar water retention values that averaged 30-fold higher than the control, while APOP and ALS-3 retained significantly less water than the surfactants with the highest water retention, with 23- and 12-fold higher soil water retention, respectively, than the control. Soil water retention in the SS-treated soil columns was fivefold higher than the control, but was similar to FA, which was statistically similar to the control.

For the majority of the products, soil water retention slightly increased or remained the same when tap water was added to the soil columns 31 d after the initial surfactant treatment (Table 4). An exception to this pattern, thus the significant interaction (Table 2), was found with soil columns treated with ALS-1 and ALS-2 at 6 mL a.s.i. L^{-1}; on average, these soil columns retained 51% less water than when they were originally treated, suggesting degradation of the surfactant during the time of the study (Table 4).

Surfactant products did not separate into such distinct groups when the columns had tap water added after 31 d as they did when the columns where first treated (Table 4). At 6 mL a.s.i. L^{-1}, EAP, PPS, AES/AAP, and APG responded similarly to each other and had the highest water retention. On average, the soil columns in this group retained 19-fold more water than the control. Unlike after the initial surfactant application, PPGP retained slightly less water than EAP but was still similar to APG, AES/AAP, and PPS, while P2B slightly improved in its ability to retain water compared with APG, AES/AAP, and PPS, although it was still less than EAP. The surfactant products NOA, ALS-2, and APOP responded similarly to each other, having on average an eightfold increase over the control in water retained in the soil, while ALS-1 was similar to APOP and ALS-2 but slightly less than NOA, and ALS-3 retained approximately fourfold more water in the soil than the control. The water retention values of FA and SS were similar to the control (Table 4).

Adding water to the soil columns that were originally treated with 12 mL a.s.i. L^{-1} also had generally similar results to when they were originally treated (Table 4). An exception to this pattern, thus the significant interaction, was found for soil columns that had originally been treated with the ALS-1 and ALS-2 surfactants. Columns treated with ALS-1 and ALS-2 dropped in their ranking compared with after the initial surfactant treatment and retained significantly less water than EAP, P2B, APG, PPS, AES/AAP, and NOA.

DISCUSSION

The products evaluated in this study generally improved water penetration into the soil and increased soil water retention; however, there was a large range in the performance of the surfactant products. The most effective products for treating soil water repellency were APG, AES/AAP, PPS, and EAP (Tables 3 and 4). The surfactant PPGT generally performed similarly to the most effective products, particularly at a higher surfactant application rate. Overall, solutions of these most effective products rapidly penetrated into the soil and increased the water-holding capacity. After the surfactant treatment, the soil was able to rewet to the same degree as when first treated with the surfactant solution. Superior performance from these products is probably associated with the surfactants' ability to lower the surface tension of the water, decrease the contact angle between the water and the soil, and increase the absorbance of water molecules onto soil particles coated with water-repellent, nonpolar organic coatings (Miller et al., 1975; Moore and Moore, 2005).

The surfactants ALS-2, ALS-1, APOP, and NOA showed an intermediate response in relationship to the other surfactant types. As with the most effective products, the APOP- and NOA-treated soils rewet to the same degree as when first treated with the surfactant solution. Soil columns treated with ALS-1 and ALS-2 retained dramatically less water when they were rewet; this reduction in water retention was unique to these products. Unlike ALS-1 and ALS-2, ALS-3 had a minimal effect on water penetration and soil water retention. It is unclear why ALS-3 did not respond similarly to ALS-1 and ALS-2 given that all three products had the same basic surfactant ingredient: ammonium laureth sulfate. Regardless, because these were the only surfactant products that included this primary ingredient, the results of this study indicate that ammonium laureth sulfate is a less effective product for the treatment of post-fire water-repellent soils. It is quite possible that the statistically significant differences between the top- and intermediate-performing surfactants used in this study will not be of practical significance in the field; however, surfactants that can increase soil water retention have a clear theoretical advantage, especially in low-rainfall landscapes.

Even at high concentrations, FA and SS were dramatically less effective than the majority of the products. These products had limited to no improvement in the amount of water retained in the soil. These data imply that these products should not be applied to treat post-fire water-repellent soil.

Several researchers have demonstrated the utility of surfactants in decreasing runoff and soil erosion (Pelishek et al., 1962; Krammes and Osborn, 1969; Valoras et al., 1974) and enhancing seedling establishment (Osborn et al., 1967; Darboux et al., 2008; Madsen et al., 2012). It can be implied that the top-performing products in this study will also be the most effective in realizing these positive effects and restoring ecohydrologic function after a wildfire. Because our study only evaluated the products performance with respect to soil water penetration and retention, however, the full utility of the products were not demonstrated in this study, particularly with respect to plant growth. For example, recent developments in soil surfactant technology have produced new patent-pending chemistries that enhance plant growth in both water-repellent and non-water-repellent soils (e.g., Kostka and Schuermann, 2008). Additional nonsurfactant ingredients are also incorporated into the commercial surfactant products. For example, ALS-2, SS, EAP, APOP, and FA claim to contain "biostimulating additives" aimed at promoting microbial activity and plant growth. Additional research is merited to understand how these and other commercially available surfactant products influence the growth of wildland plant species after a wildfire.

CONCLUSIONS

The results of this study show that the effectiveness of surfactants for improving soil water penetration and the water-holding capacity of post-fire water-repellent soils varies by product and chemistry. The most effective products for treating soil water repellency included Irrigaid Gold (APG), Advantage (AES/AAP), Penn Wetting (PPS), Pervaide (EAP), and Tournament Ready (PPGP). When these products were mixed with water, the solution was able to rapidly infiltrate into water-repellent soils. After this initial treatment, the most effective products were able to retain between 15- and 20-fold more water in the soil when they were rewet than untreated soil. Overall, this group of products responded similarly to each other.

At high concentrations, Intake (ALS-2), Attain FC (ALS-1), Wet-Sol Gro (APOP), and EZ Wet (NOA) were also effective at treating soil water repellency, but they showed an intermediate response at low surfactant concentrations. Even at high concentrations, Fulmax (FA), PenaTron (SS), and Penex (ALS-3) were less effective than the majority of the products.

In several parts of the world, wildfire activity has markedly increased, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons (Westerling et al., 2006). There is an urgency to develop ecological restoration tools to mitigate wildfire hazards. The findings from this study provide justification for the evaluation of surfactant chemistries for the management of soil water repellency after wildfire, which may help reduce increased runoff and erosion.

ACKNOWLEDGMENTS

Funding for this research was provided by Brigham Young University, USDA-National Institute of Food and Agriculture's Rangeland Research Program, and the USDA-ARS. We are grateful to Jarod Lemos and April Hulet for reviewing earlier versions of this manuscript. We also appreciate the thoughtful reviews by the anonymous reviewers and Associate Editor.

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