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Anchor Chaining's Influence on Soil Hydrology and Seeding Success in Burned Piñon-Juniper Woodlands

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ABSTRACT

Broadcast seeding is one of the most commonly applied rehabilitation treatments for the restoration of burned piñon and juniper woodlands, but the success rate of this treatment is notoriously low. In piñon-juniper woodlands, postfire soil—water repellency can impair seeding success by reducing soil—water content and increasing soil erosion. Implementing anchor chaining immediately after seeding can improve establishment of seeded species by enhancing seed-to-soil contact and may improve restoration success by decreasing soil—water repellency through soil tillage. The objectives of this research were to 1) determine if anchor chaining in postfire pinyon-juniper woodlands diminishes soil—water repellency, and 2) determine meaningful relationships between soil—water repellency, unsaturated hydraulic conductivity [$K(h)$], and the establishment of seeded and invasive species. Research was conducted on two study sites, each located on a burned piñon-juniper woodland that had severe water repellency and that was aerially seeded. At each location, plots were randomly located in similar ecological sites of chained and unchained areas. At one location, anchor chaining considerably improved soil hydrologic properties, reducing the severity and thickness of the water-repellent layer, and increasing soil $K(h)$ 2- to 4-fold in the first 2 yr following treatment. At this same location, anchor chaining increased perennial grass cover 16-fold and inhibited annual grass and annual forb cover by 5- and 7-fold, respectively. Results from the second site only showed improvements in soil $K(h)$; other hydrologic and vegetative treatment responses were not significantly improved. Overall, this research suggests that anchor chaining has the potential to improve restoration outcomes, though additional research is warranted for understanding the direct impact of anchor chaining on soil—water repellency without the interaction of a seeding treatment.

Introduction

Sagebrush (*Artemisia* spp.) ecosystems of western North America are rapidly declining (Davies et al., 2011). The expansion of piñon (*Pinus* ssp.) and juniper (*Juniperus* spp.) woodlands (Davies et al., 2011) represents a significant component in the loss of sagebrush communities. Estimates show that piñon-juniper woodlands currently occupy 40 million hectares (Romme et al., 2009). This represents a 10-fold increase from the pre-European settlement period (Miller and Tausch, 2001). As these woodlands mature, fuel loads and tree canopy cover increase, promoting large-scale, high-intensity wildfires (Miller and Tausch, 2001; Miller et al., 2008). The loss of shrubs and perennial grasses associated with advanced tree infilling and high-intensity fire reduce ecosystem resilience (Miller and Tausch, 2001; Miller et al., 2008). Lack of perennial shrubs and grasses encourages a shift to an introduced annual weed community (Bestelmeyer et al., 2009; Miller and Tausch, 2001). The domination by invasive annuals, such as cheatgrass (*Bromus tectorum* L.), increases the frequency and scale of wildfires, which further promotes invasion (D'Antonio and Vitousek, 1992); with this conversion, hundreds of sagebrush obligate species are declining or at risk of extirpation (Rowland et al., 2006). Loss of native vegetation is also affecting rangeland ecosystem goods and services, including national and regional food supplies, water quality, and recreation (Brunson and Tanaka, 2011).

Land managers can halt the shift to an introduced nonnative annual community by successfully seeding desired perennial species after a wildfire (Goodrich and Rooks, 1999; Ott et al., 2003). Where economic and site conditions allow, a rangeland drill can effectively distribute and sow seeds of perennial species (Monson et al., 2004). However, the presence of tree skeletons or steep and rocky soils can prohibit the use of a rangeland drill on many sites. Under these conditions, land managers are constrained to aerial broadcast seeding (Vallentine, 1989; Whisenant, 1999).

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In low elevation (i.e., < 2 000 m) sagebrush communities where precipitation levels are low, broadcast seeding will often result in poor establishment of a perennial plant community (Allen, 1995; Lysne and Pellant, 2004; Ott et al., 2003; Tausch et al., 1995). With adequate precipitation, anchor chaining can improve the success of broadcast seeding efforts when implemented directly after the seeds are sown (Juran et al., 2008; Ott et al., 2003; Thompson et al., 2006). Anchor chaining is performed by pulling a 60—120-m—long anchor chain with 20—40-kg links between two heavy, continuous-tracked tractors traveling in the same direction. Swivels attached at both ends of the chain allow it to rotate and till the soil. Welding short 30—40-kg lengths of railroad iron across each link further increases disturbance; this type of chain is referred to as an “Ely Chain” (Cain, 1971; Fig. 1). Improvement in seeding success from anchor chaining has been primarily attributed to the technique’s ability to 1) cover the seed (Ott et al., 2003), 2) increase the number of seed “safe sites” (Harper et al., 1965; Ott et al., 2003; Thompson et al., 2006), and 3) increase infiltration rates and decrease soil loss and sedimentation levels resulting from the redistribution of debris material from the burned trees (Roundy and Vernon, 1999).

Postfire anchor chaining may also improve seeding success by mitigating the effects of soil—water repellency as this condition is well documented in piñon-juniper woodlands (Jaramillo et al., 2000; Madsen et al., 2008; Madsen et al., 2012a; Roundy et al., 1978; Scholl, 1971; Zvirzdin, 2012). Although soil—water repellency is often present prior to fire, burning can increase its severity and spatial consistency (Doerr et al., 2000). During a fire, heat volatilizes hydrophobic molecules in the litter and upper soil layers; pressure gradients then force the material deeper into the soil where it condenses upon the cooler underlying soil particles (DeBano et al., 1976). This process of volatilization and condensation can intensify water repellency by increasing the continuity of hydrophobic substances across the profile (Letey, 2001) and changing the nature of these substances, such that they bind tighter to soil particles and repel water more effectively (Doerr et al., 2009). The most clearly shown effect of soil—water repellency is the negative relationship between soil—water repellency and infiltration (DeBano, 1971; Doerr et al., 2003; Madsen et al., 2011; Pierson et al., 2008). The reduction of water infiltration by soil—water repellency has many secondary effects, including reduced soil—water content near the soil surface (Madsen et al., 2011, 2012a; Wallis et al., 1990) and increased runoff and erosion (Benavides-Solorio and MacDonald, 2001; DeBano and Rice, 1973; Leighton-Boyce et al., 2007; Martin and Moody, 2001). Decreased soil moisture content and site stability impairs seeding efforts by reducing seed germination and establishment success (Letey, 2001; Madsen et al., 2012a; Wallis et al., 1990).

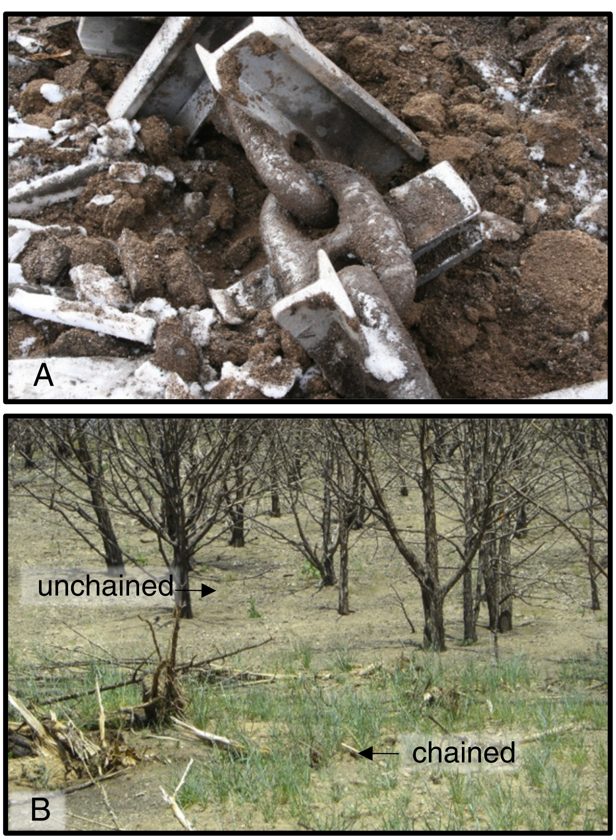

Fig. 1. A, Photo showing soil tillage created by an Ely-style anchor chain, and **B,** revegetation success between chained and unchained sites 2 yr after the Cedar Fort wildfire in Utah.

Observations by land management personnel have attributed improvements in restoration success from anchor chaining to the ability of the practice to disrupt the water-repellent layer with the tilling action of the chain (Utah State Legislature Natural Resources, Agriculture, and Environment Interim Committee, 1997). However, research is lacking that verifies this hypothesis and examines the mechanisms by which anchor chaining improves seedling germination and establishment in the presence of water-repellent soils.

The objectives of this research were to 1) determine if anchor chaining in postfire piñon-juniper woodlands diminishes soil—water repellency; and 2) determine meaningful relationships between soil—water repellency, hydraulic conductivity, and the establishment of seeded and invasive species. We hypothesize that anchor chaining will reduce soil—water repellency levels, which will increase soil hydraulic conductivity, and aid in the establishment of seeded perennial species and prevention of non-native annual weeds.

Methods

Study Site Description

We established study sites at the Cedar Fort and Milford Flat wildfires, located in central and south-central Utah, USA, respectively. The Cedar Fort fire was ignited by lightning on 3 August 2007 and burned 9 500 ha. Research at the Cedar Fort fire was conducted 4.3 km North of Cedar Fort, UT, USA (Lat: 40° 22' 10" N, Long: 112° 6' 6" W, elevation 1 841 m). The research site is predominantly southwest facing, and at the base of the Oquirrh Mountain Range. Prior to the fire, the plant community was in a Phase III juniper woodland development phase (Miller et al., 2008), with Utah juniper (*Juniperus osteosperma* [Torr.] Little) acting as the primary plant driving ecological processes. Soil parent material is alluvium derived from limestone and sandstone and is loamy-skeletal, carbonatic, mesic, shallow Petrocalcic Palexerolls (2—8% slope) (Soil Survey Staff, 2009). Soil pH is 8.5, organic matter content 1.5%, volumetric soil—water content at -1.5 MPa (permanent wilting point) and -0.33 MPa (field capacity) is equal to 6.2%, and 17.5%, respectively. Mean annual precipitation is approximately 330 mm (Soil Survey Staff, 2009). In October 2007, the State of Utah aerially seeded the site and portions of the fire boundary were anchor-chained with a single pass by an Ely-style chain. A seed mix of native and introduced species was applied at 13 $kg \cdot ha^{-1}$ of bulk seed. Particularly for the more arid and/or degraded sites in the Great Basin, nonnative species are commonly included in the seed mix to aid in soil stabilization and weed control (Monson et al., 2004). At this site, the native shrub Wyoming big sagebrush (*Artemisia tridentata* Nutt. spp. *wyomingensis* Beetle & Young) was sown. Native grasses seeded included slender wheatgrass (*Elymus* *trachycaulus* [Link] Gould ex Shinners), and bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve). Introduced grasses included crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), orchardgrass (*Dactylis glomerata* L.), and intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R.). Native forbs sown were common yarrow (*Achillea millefolium* [L.]), and gooseberry globemallow (*Sphaeralcea grossulariifolia* [Hook. & Arn.] Rydb.). Introduced forbs included alfalfa (*Medicago sativa* [L.]), sainfoin (*Onobrychis viciifolia* Scop.), and small burnet (*Sanguisorba minor* Scop.).

Lightning ignited the Milford Flat fire on 6 July 2007 and burned 145 000 ha, making it the largest fire in Utah's recorded history. Our research site on the Milford Flat fire was 13.7 km NE of Milford, UT, USA (Lat: 38° 26' 12" N, Long: 112° 51' 46" W, elevation 1 847 m). This site, positioned at the base of the Mineral Mountain Range, has predominantly west-facing slopes. Prior to the fire, the plant community was a Phase III piñon-juniper woodland development phase (Miller et al., 2008), with Utah juniper and singleleaf piñon (*Pinus monophylla* Torr. & Frém.) acting as the primary plant types driving ecological processes. Soil parent material is alluvium derived from intermediate igneous rock (granite), with soils classified as coarse sandy loam, mixed, mesic Aridic Haploxerolls (3—10% slope). Soil pH is 7.6, organic matter content 2.3%, volumetric soil—water content at −1.5 MPa (permanent wilting point) and −0.33 MPa (field capacity) is equal to 12.8%, and 24.8%, respectively (Soil Survey Staff, 2009). Mean annual precipitation is approximately 370 mm (PRISM Climate Group, 2012). In November—December 2007, the U.S. Bureau of Land Management and the State of Utah aerially seeded the site, and portions of the fire boundary were anchor-chained with a single pass by an Ely-style chain. A seed mix of native and introduced species was applied at 14.8 $kg \cdot ha^{-1}$ of bulk seed. Native grasses included western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Love), thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & J.G. Sm.] Gould ssp. Lanceolatus), and mountain brome (*Bromus marginatus* Nees ex Steudel). Nonnative seeded grasses were pubescent wheatgrass (*Agropyron trichophorum* [Link] Richter), intermediate wheatgrass, and Siberian wheatgrass (*Agropyron fragile* [Roth] Candargy). Native forbs were not seeded; introduced forbs included blue flax (*Linum perenne* L.), small burnett, Sainfoin, and alfalfa.

We observed at both the Cedar Fort and Milford Flat fires that the sites were almost completely denude of vegetation after the fire. This is most likely the result of the severity of the wildfires, but our observations in unburned sites near the burned area also indicated that competition of the phase III woodland had outcompeted much of the understory vegetation. We also observed in the anchor-chained areas at both Cedar Fort and Milford Flat fires that the trees were completely knocked over, but were not moved from their individual locations. Soil tillage was noted to greater than a 10-cm depth because of the tilling action of the anchor chain (Fig. 1). Disturbance was further created in the soil as roots were uplifted near the base of the trees when the anchor chain tipped them over. Long-term and monthly precipitation estimates during the period of the study were derived for each site from models developed by PRISM's Oregon Climate Service (PRISM Climate Group, 2012) (Fig. 2). Annual precipitation over a 30-y period was estimated from 1970–2000.

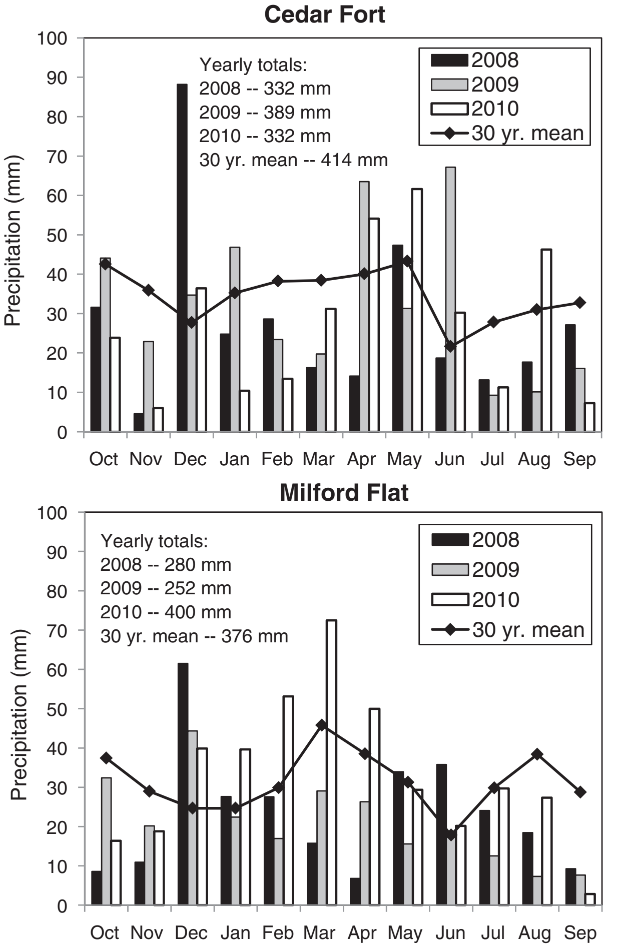

Fig. 2. Total monthly precipitation over the 3 yr of the study (2008–2010) and 30-yr average precipitation (1970–2000) for Cedar Fort and Milford Flat study areas in Utah. Data was derived from models developed by PRISM's Oregon Climate Service.

Experimental Design

We implemented a paired plot design at each research location (Cedar Fort and Milford Flat fires) for comparing anchor-chained and unchained areas. At each research location permanent plots were established along a roughly 120-m transect that bisected anchor-chained and unchained sites. Along the transect, five areas were identified that had trees growing prior to the fire within similar site conditions (i.e., soils, slope, and aspect). Each of these areas was considered a block. We then selected all suitable trees within each block out to a distance of approximately 20 m from the anchor-chained and unchained boundary. Suitable trees were considered to be mature, severely burned, and did not have obstacles that would hinder sampling such as nearby trees, rocks, washes, or gullies. Of the trees identified in each block, we randomly selected one tree from each of the chained and unchained locations. This study design resulted in five trees each being sampled in the chained and unchained areas.

Plots 2.0 m in radius (area 12.6 m^2) were centered on the trunk of the randomly selected trees. A plot radius of 2.0 m was chosen because most preburn canopies in the study area extended approximately this distance; as estimated from remaining tree branches and burned litter material at the soil surface. Research was focused on the canopy area because this is the area where the effects of soil repellency are expected to be greatest (Madsen et al., 2008, 2012a, 2012b, 2012c; Zvirzdin, 2012).

Measurements

We sampled the same plots in July 2008, 2009, and 2010. Severity and depth of soil—water repellency, soil unsaturated hydraulic conductivity [$K(h)$], and vegetation cover and density were measured in each plot. Soil—water repellency and $K(h)$ measurements were taken along two radial line transects that extended from the trunk of the tree in two random directions. Along the line transect, measurements were taken at 0.6, 1.2, and 1.8 m from the center of the trunk (i.e., the center of the plot), for six sampling points per plot. We measured unsaturated hydraulic conductivity at each sampling point with automated mini-disk infiltrometers (Madsen and Chandler, 2007). We assessed water repellency severity using the water drop penetration time (WDPT) test, with soils considered water repellent if WDPT exceeded 5 s (Ritsema et al., 2008). The thickness of the water-repellent layer was identified by placing a water drop at 0.5 cm increments from the soil surface down to approximately 80 cm to delineate the upper and lower limits. Both chained and unchained areas were sampled the same; if ash material was present, this material was counted as being part of the depth to the water-repellent layer. For soils that had *in situ* WDPT's that exceeded 1 min, we collected a sample of soil for analysis of severity using the WDPT test in the lab (37% and 68% of the samples from Cedar Fort and Milford Flat fires were analyzed for WDPT in the lab, respectively). Soil samples were collected by using a spatula to carefully remove approximately 40 g of soil from the water-repellent layer. Because these soil measurements disturbed the soil, a wire flag was left at the sample location so the following yr's measurements did not occur in the same place.

In the first yr after seeding, vegetation was sparse; therefore, to obtain meaningful information on species density and cover, we conducted a census of the entire plot by counting all plants in the plot and estimating cover of each individual plant. In the second and third yr of the study, we visually estimated vegetation cover and density by species inside 24 randomly placed 0.125 m^2 quadrats. To aid in the placement of the quadrats, a portable wire frame was made to cover approximately half of the plot, and had individual grids that were 0.25 × 0.5 m. Within the frame, 24 of the individual grids were randomly marked for use as sample locations. The orientation of the frame in relationship to the tree's trunk was randomly chosen at each tree.

Data Analysis

Soil hydrology and vegetation data were analyzed using repeated measure mixed-model analysis with a compound symmetry covariance structure in SAS (Version 9.2; SAS Institute, Cary, NC, USA). In the model, we considered site and treatment (chained or unchained control) as fixed, yr of measurement as a repeated measure, and blocks within sites and treatments × blocks within sites as random. We analyzed vegetation response after we grouped plant density and cover readings into five functional classes: perennial bunchgrass, annual grass, perennial forbs, annual forbs, and shrubs. We did not analyze perennial forb and shrub data because they composed < 1% of the total cover and density. When we found significant main or interactive effects, we separated mean values using pairwise T-tests, with a Bonferroni adjustment. Prior to analysis, we tested for normality and homogeneity using the Shapiro-Wilk and Levene's tests, respectively. To reduce problems with deviance from normality, we square-root—transformed WDPT data, log-transformed $K(h)$ and plant density data, and cube-root—transformed plant cover data. For all comparisons, a significance level of $P < 0.10$ was used. In the text and figures, we reported mean untransformed values with associated standard errors.

Table 1
Results from repeated measures mixed model analysis comparing soil hydrologic and vegetation parameters between anchor-chained and unchained treatments, at two different locations (Cedar Fort and Milford Flat fires), over a 3-yr survey period (2008-2010).

Soil hydrology						
Source	WDPT[1]		WR[2] thickness		K(h)[3]	
	F	Pr > *F*[4]	*F*	Pr > *F*	*F*	Pr > *F*
Treatment	13.09	**0.007**	8.66	**0.010**	13.41	**0.006**
Location	10.24	**0.013**	8.29	**0.011**	3.41	0.102
Year	7.64	**0.002**	19.48	<**0.001**	58.84	<**0.001**
Treatment X location	0.22	0.648	0.00	0.986	0.75	0.411
Treatment X year	0.79	0.464	0.40	0.671	0.74	0.485
Location X year	4.92	**0.014**	5.18	0.011	0.03	0.966
Treatment X location X year	2.06	0.145	0.06	0.942	0.86	0.434
Plant density						
Source	Perennial grass		Annual grass		Annual forb	
	F	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*
Treatment	20.97	**0.002**	1.27	0.277	7.31	**0.016**
Location	12.82	**0.007**	0.65	0.431	12.69	**0.003**
Year	26.21	<**0.001**	25.98	<**0.001**	29.11	<**0.001**
Treatment X location	10.36	**0.012**	8.00	**0.012**	2.11	0.166
Treatment X year	12.49	<**0.001**	0.71	0.498	7.74	**0.002**
Location X year	15.67	<**0.001**	0.58	0.564	12.31	<**0.001**
Treatment X location X year	6.50	**0.004**	7.53	0.002	2.03	0.147
Plant cover						
Source	Perennial grass		Annual grass		Annual forb	
	F	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*
Treatment	7.87	**0.023**	3.29	**0.089**	5.12	**0.038**
Location	5.54	**0.046**	0.21	0.655	22.90	<**0.001**
Year	16.19	<**0.001**	85.89	<**0.001**	36.15	<**0.001**
Treatment X location	0.98	0.352	7.60	**0.014**	3.18	**0.093**
Treatment X year	3.43	**0.045**	7.34	**0.002**	6.92	**0.003**
Location X year	0.96	0.395	5.05	**0.012**	15.52	<**0.001**
Treatment X location X year	0.18	0.840	3.95	**0.029**	2.61	**0.089**

[1] Water drop penetration time
[2] Water repellency
[3] Unsaturated hydraulic conductivity
[4] Significant P values are highlighted in bold (P < 0.10)

Results

Precipitation

At Cedar Fort, yearly precipitation estimates was approximately 80, 93, and 80% of the long-term average in 2008, 2009, and 2010, respectively (Fig. 2). Precipitation that occurred during the period most typical for seedling emergence and seedling growth (March—June) was below average (between 35—87% of the long-term average) on most months in the first yr, with the exception of the month of May, which was 110% of long-term average. In the second and third yr, precipitation during March—June was generally above average. Yearly precipitation at Milford Flat was 75, 67, and 106% of the long-term average for 2008, 2009, and 2010 respectively. At this site, precipitation from frontal storms is typically high in the early spring. This was not the case in March and April for the first yr after seeding; precipitation was 34 and 18% of the long-term average, respectively. May precipitation was average, while June was twice that of the long-term average. In the second yr, precipitation during the growing season was below average for all months except June. In the third yr, precipitation was generally above the long-term average.

Soil Hydrology

Analysis across all years and locations showed that anchor-chained plots had a decrease in the severity and thickness of the water-repellent soil and increased soil $K(h)$, with the degree of change varying by location and sampling yr (Table 1). At Cedar Fort, the thickness and severity of water-repellent soil was similar

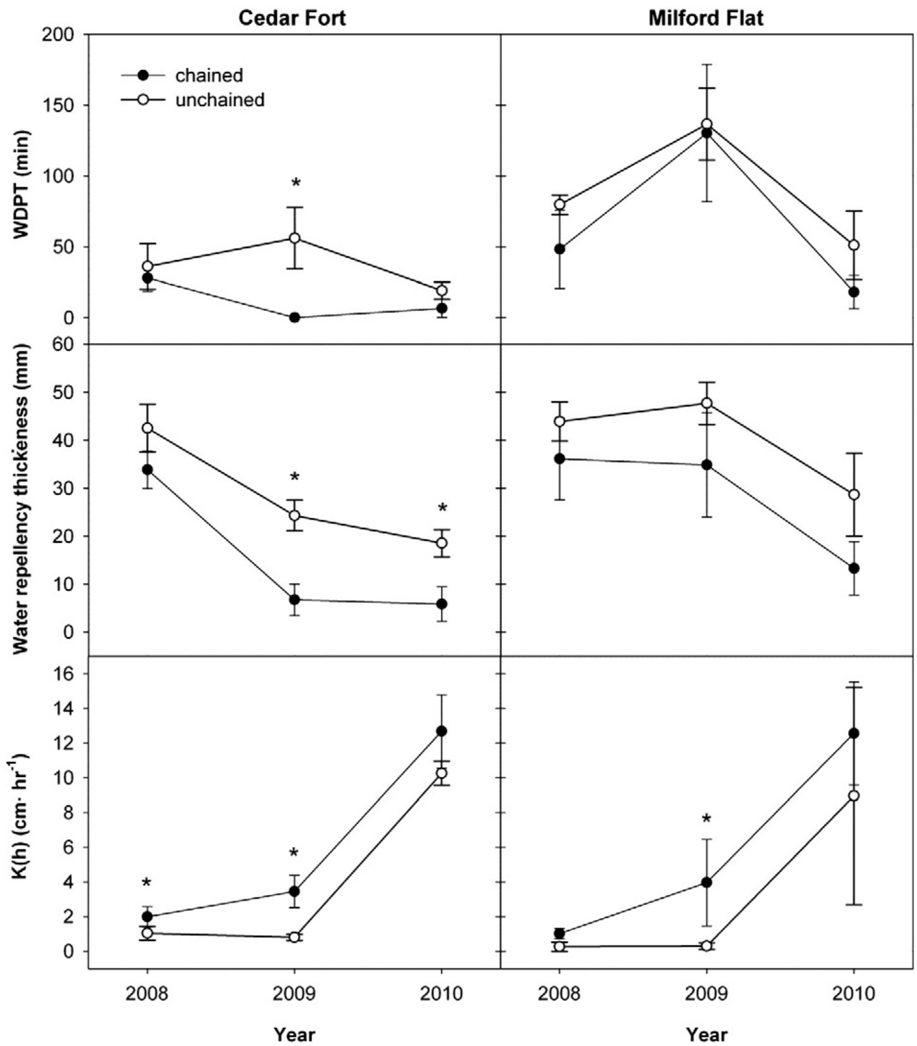

Fig. 3. Water drop penetration time (WDPT), water repellency thickness, and unsaturated hydraulic conductivity [$K(h)$] for anchor-chained and unchained treatments at Cedar Fort and Milford Flat study sites over a 3-yr period. *Asterisk denotes significant differences between treatments (Bonferroni, $P < 0.10$).

between treatments the first yr after seeding, with an average WDPT of 31.9 ± 8.8 min and water repellency thickness of 38.2 ± 3.3 mm (Fig. 3). In the second yr, water repellency at Cedar Fort was nearly absent in the chained treatment (average WDPT 7.0 ± 3.0 s and thickness 6.7 ± 3.3 mm), while unchained severity was similar to the previous yr and thickness of the water-repellent layer was slightly reduced. In the third yr, the severity of the water-repellent layer in the unchained treatment showed some dissipation and was statistically similar to the anchor-chained plots. The water-repellent layer remained significantly thicker in the unchained treatment compared with the anchor-chained treatment in the third yr. Overall, the thickness of the water-repellent layer declined over time in both chained and unchained treatments.

Soil $K(h)$ at Cedar Fort in the anchor chaining treatment was approximately 2- and 4-fold higher in the first and second yr compared with unchained (Fig. 3). In yr 3, soil $K(h)$ increased in both anchor-chained and unchained plots and was similar between the treatments. Within both treatments soil $K(h)$ increased over the period of the study, particularly in the third yr.

At Milford Flat, severity and thickness of soil—water repellency were similar across chained and unchained treatments (Fig. 3). Soil $K(h)$ was also similar between treatments in the first yr. As with Cedar Fort, improvements in soil hydrology were seen in the second yr, with the anchor-chaining treatment having over 13-fold higher soil $K(h)$ than the unchained treatment. In yr 3, differences between anchor-chained and unchained plots were no longer significant, due in part to high variability, which most likely was associated with the natural dissipation of soil—water repellency. Similar to the Cedar Fort fire a decline in the thickness of the water-repellent layer and an increase in soil $K(h)$ was shown overtime in both chained and unchained treatments.

Vegetation Density and Cover

Treatment, location, and sampling yr influenced the density and cover of perennial grasses (Table 1). There were also significant two- and three-way interactions among these parameters indicating that the influence of the anchor-chaining treatment varied by site and sampling yr.

At Cedar Fort, perennial grass density in the first yr was minimal in the unchained treatment with 0.19 ± 0.2 plants m^{-2}, whereas the anchor chaining treatment had 5.35 ± 2.3 plant·m^{-2} (28-fold difference) (Fig. 4). In the second yr, differences remained distinct between the treatments. In the third yr, plant density had increased significantly to 5.7 ± 2.6 plants·m^{-2} in the unchained treatment

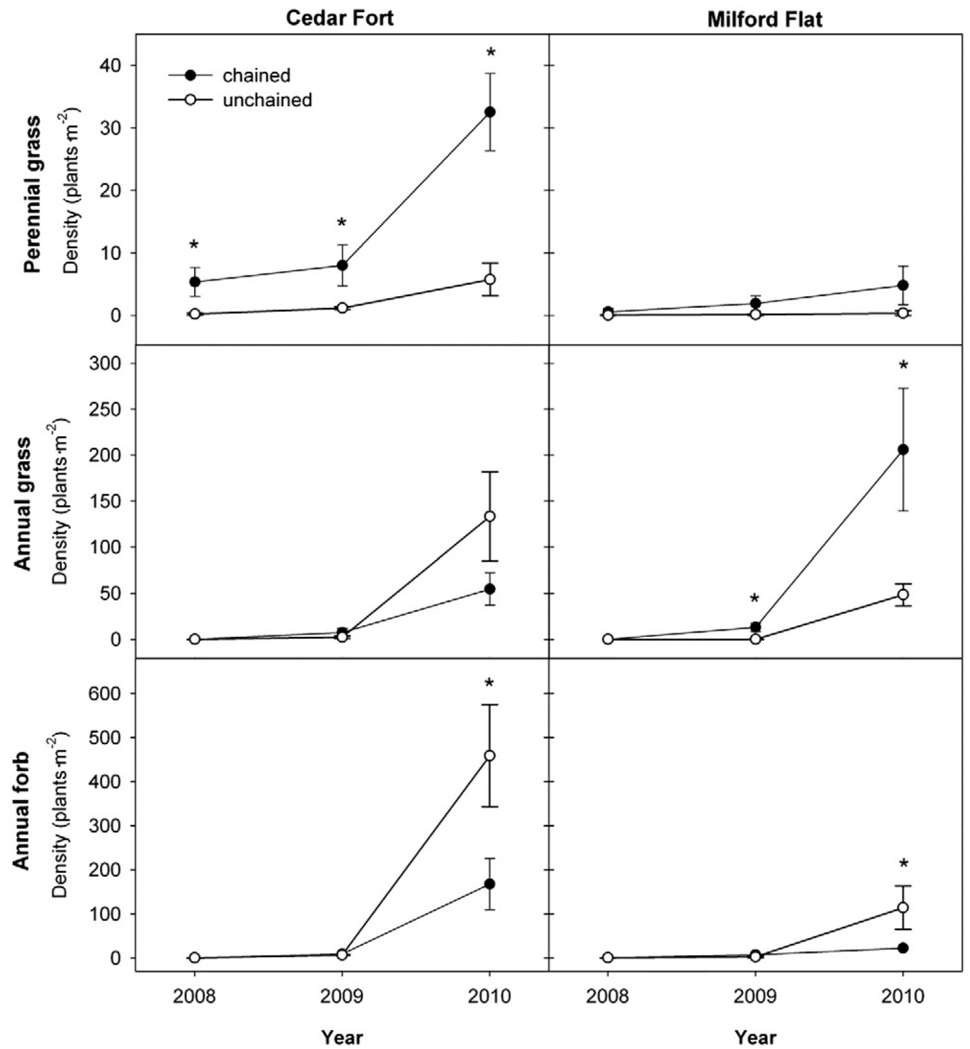

Fig. 4. Density of perennial grasses, annual grasses, and annual forbs for anchor-chained and unchained treatments at Cedar Fort and Milford Flat study sites over a 3-yr period. *Asterisk denotes significant differences between treatments (Bonferroni, $P < 0.10$).

and 32.5 ± 6.2 plants·m^{-2} in the anchor chaining treatment, a 6-fold difference.

Perennial grass cover at Cedar Fort in the first yr was minimal and similar between the anchor-chained and unchained treatments, with cover at the site averaging 0.3 ± 0.2% (Fig. 5). Perennial grass cover in the unchained treatment remained low throughout the study. In the anchor-chained treatment, perennial grass cover increased significantly to 6.2 ± 2.8% in yr 2, which resulted in the anchor-chained treatment having a 16-fold increase over the unchained treatment. Cover for both treatments did not change significantly between the second and third yr.

Seeding success of perennial grasses at Milford Flat was poor for both chained and unchained treatments. At this location, perennial grass density and cover were similar between treatments across all 3 yr (Figs. 4 and 5). Annual grass density and cover varied greatly by sampling yr for both locations (Table 1). There was also a significant interaction between treatment and location for annual grass density and significant 2- and 3-way interactions between treatment, location, and yr sampled. In the first yr after the fire, annual grasses were sparse at both study locations (Figs. 4 and 5). In yr 2 and 3, differences in the influence of the anchor-chaining treatment between locations became apparent. At Cedar Fort, annual grass density remained low for 2 yr after the fire and then increased in yr 3 (Fig. 4). Annual grass cover also followed a similar trend as plant density, but in the third yr, treatments were significantly different, with the unchained treatment having 5-fold higher cover than the chained treatment (13.4 ± 5.4% cover in unchained vs. 2.5 ± 1.1% cover in the anchor-chained treatment) (Fig. 5).

Anchor chaining did not inhibit annual grass invasion at Milford Flat. There is some evidence that anchor chaining increased annual grass density. This is more evident in the third sampling yr where annual grass density is 4-fold higher in the chained treatment compared with unchained (206.5 ± 66.6 plants·m^{-2} in the chain treatment vs. 48.5 ± 12.2 plants·m^{-2} in unchained) (Fig. 4). However, at this site annual grasses were the dominant vegetation in both treatments, with cover values of annual grasses in the third yr similar between treatments.

In general, treatment, location, sampling yr, and their interactions influenced annual forb density and cover (Table 1). At Cedar Fort, annual forb density was similar between treatments during the first and second yr of the study, with 0.06 ± 0.03 and 7.58 ± 1.38 plants·m^{-2}, respectively (Fig. 4). In the third yr, the density of annual forbs increased to 167.5 ± 58.3 plants·m^{-2} in the anchor-chain treatment and 458.8 ± 116.1 plants·m^{-2} in unchained, resulting in a 3-fold difference between the treatments. Annual forb cover was also low in the first yr after the fire (0.08 ± 0.1%) (Fig. 5). In the

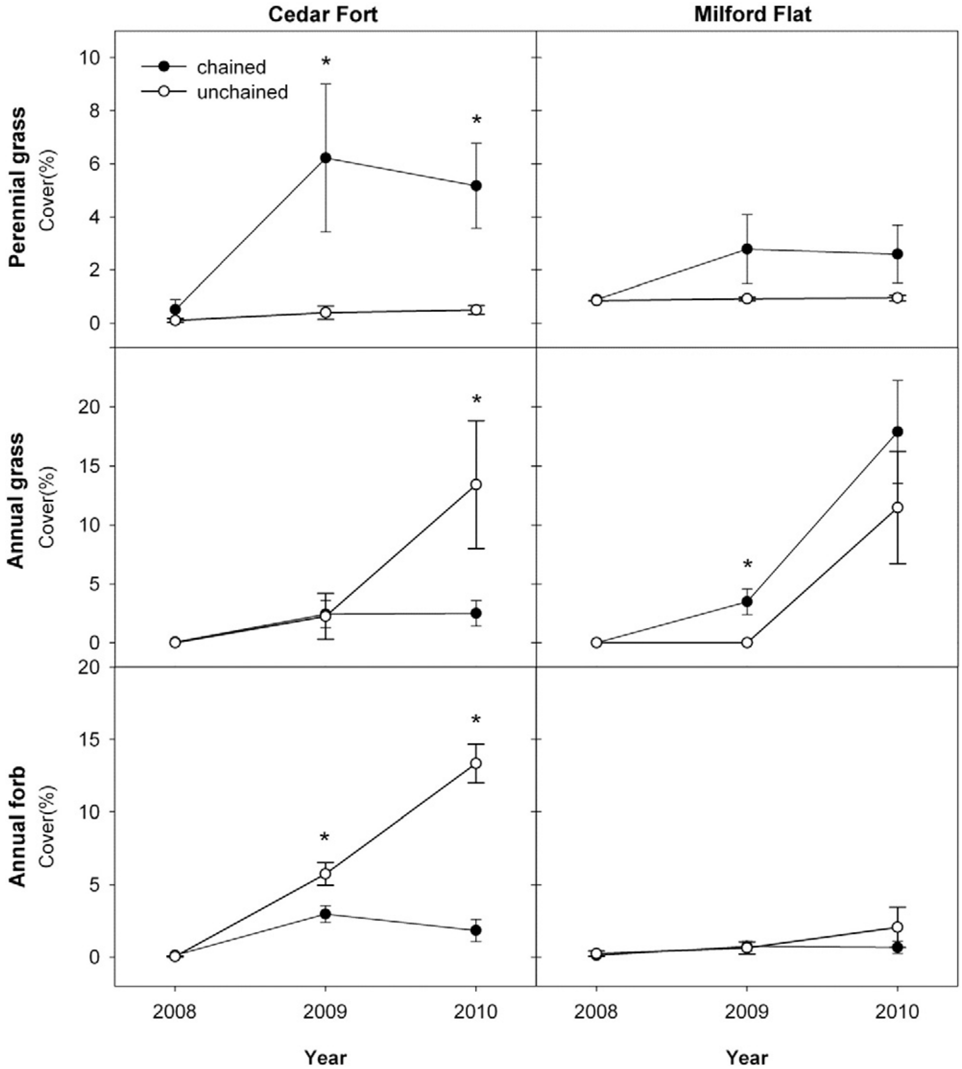

Fig. 5. Percent cover of perennial grasses, annual grasses, and annual forbs for anchor-chained and unchained treatments at Cedar Fort and Milford Flat study sites over a 3-yr period. *Asterisk denotes significant differences between treatments (Bonferroni, $P < 0.10$).

second yr, cover in the unchained treatment was 2-fold higher than the anchor-chained treatment, with 5.7 ± 0.8% and 3.0 ± 0.6% cover, respectively. In the third yr, annual forb cover was 7-fold higher in the unchained treatment compared with the anchor-chaining treatment (1.8 ± 0.8% in unchained vs. 13.3 ± 1.3% in the anchor-chain treatment).

Overall, annual forb density and cover at Milford Flat was lower than Cedar Fort, but the relative response between the treatments was somewhat similar for forb density. In the first 2 yr of the study, annual forb density and cover were near zero at Milford Flat (Figs. 4 and 5). In the third yr, annual forb density in the unchained treatment increased 5-fold relative to the chaining treatment (113.9 ± 42.3 plants·m^{-2} in the unchain treatment vs. 22.0 ± 3.2 plants·m^{-2} in the chain treatment) (Fig. 4). Annual forb cover at Milford Flat was relatively low and statistically similar between the treatments over the period of the study.

Discussion

Our hypotheses that anchor chaining would 1) improve soil hydraulic properties by decreasing the level of water repellency in the soil, 2) increase establishment of seeded species, and 3) prevent the site from transitioning to an nonnative annual dominated system was supported to some degree, with the degree of response from the anchor chaining treatment varying by location. Results obtained from Cedar Fort supported our hypotheses. In this study, reductions in soil—water repellency through anchor chaining were most pronounced in the second yr after treatment; this may indicate that disturbance of the soil through anchor chaining initiated processes that degraded water repellency overtime. We observed that a form of soil tillage had occurred with the movement of the anchor chain across the site and with the uprooting of trees. These results are consistent with findings in the agricultural sector where soil tillage practices tend to reduce water repellency levels in soil, compared with untilled soils (Blanco-Canqui and Lal, 2009). The suspected mechanisms by which tillage may lower water repellency levels include dilution of repellent topsoil with nonrepellent soil (Holzhey, 1969), removal of hydrophobic coatings by the abrasion of soil particles (Wallis et al., 1990), and acceleration of soil organic matter decomposition rates (Blanco-Canqui and Lal, 2009; Harper et al., 2000). In addition to soil tillage, impressions created near the soil surface and scattered tree debris could increase and enhance water infiltration into the soils and subsequently promote the dissipation of soil—water repellency. Several authors have documented a reduction in soil—water infiltration in piñon-juniper woodlands because of antecedent or fire-induced water repellency (Madsen et al., 2008; Madsen et al., 2011; Pierson et al., 2011; Robinson et al., 2010). The ability of anchor chaining to decrease the severity and thickness of the water-repellent layer may be one reason $K(h)$ was 2- to 4-fold higher in the anchor-chained plots compared with unchained plots in the first 2 yr after the Cedar Fort fire. The positive feedback cycle that exists between plant density and water infiltration also most likely contributed to greater soil $K(h)$ observed in the chained plots. While not quantifiable through our measurements with tension infiltrometers, woody debris over the soil surface may have enhanced infiltration in the anchor-chained plots. Previous work has shown that woody debris can decrease raindrop impact and reduce surface runoff (Cline et al., 2010; Davenport et al., 1998).

Perennial vegetation response at Cedar Fort was consistent with previous research demonstrating improved postfire seeding success through anchor chaining (Juran et al., 2008; Ott et al., 2003; Thompson et al., 2006). Amelioration of postfire soil—water repellency by using nonionic surfactants has also been associated with improved plant establishment after a wildfire (DeBano et al., 1967; Osborn et al., 1967; DeBano and Rice, 1973; Madsen et al., 2012a and b). Results may suggest that the treatment of soil—water repellency through anchor chaining may influence soil hydrologic properties similar to application of surfactants, despite the mechanistic differences between the two treatments. Results of this study help verify a greenhouse study by Madsen et al. (2012c) where soil—water repellency was treated through either application of soil surfactants or a simulated anchor-chaining treatment. Madsen et al. (2012c) showed that both the application of soil surfactants and simulated anchor chaining were effective at improving plant growth in water-repellent soil. Madsen et al. (2012c) and other wildland studies in different systems where water repellency had been treated (e.g., Debano and Conrad, 1974; Krammes and Osborn, 1969; Osborn et al., 1967) attribute enhanced plant performance, at least in part, to improved soil hydrologic function. With the reduction of soil—water repellency, seed germination and plant survival are improved as soils are more stable and the amount of available water is increased because water can more uniformly wet the soil profile (Dekker and Ritsema, 2000; Madsen et al., 2012b).

This study, however, does not definitively prove that a reduction in soil—water repellency through anchor chaining was the primary reason for enhanced plant establishment of seeded species. Adequate seed—soil-contact and microsite placement is critical for successful seeding of arid rangeland systems (Monson et al., 2004). A potentially even more important mechanism for improved plant establishment could be due to the anchor-chain covering the seed with soil and creating safe-sites that are more conducive to seed germination and plant growth (Harper et al., 1965; Ott et al., 2003; Thompson et al., 2006). This study also does not definitively prove that anchor chaining directly promoted the dissipation of soil—water repellency. Anchor chaining's ability to improve plant establishment may also be contributed to soil—water repellency decline, as vegetation could improve soil infiltration (HilleRisLambers et al., 2001) and subsequent breakdown of soil—water repellency.

In our study, anchor chaining was associated with a substantial inhibition in annual grasses and forbs at the Cedar Fort site where seeding was most successful. This inhibition in annuals through anchor chaining is most likely tied to increased perennial grass establishment and associated decreased resource availability to annuals. Throughout much of the Great Basin, exotic plant species are present, but established perennials limit their expansion and dominance (Davies, 2008; Davies et al., 2010). Disturbance by high-intensity (or catastrophic) wildfires has been shown to increase resource availability (Chambers et al., 2007; Hemstrom et al., 2002). While nonnative annual plant densities may be low during the first yr after fire, enhanced resource availability and reduced competition provide a window for the rapid domination of the site (Monaco et al., 2003; Young and Evans, 1978). The unchained treatment of our study illustrates this general response, with annuals rapidly expanding the second and third yr after fire. While this was only a 3-yr study, trends in our data and results of previous studies suggest that annual plant cover (particularly cheatgrass) will continue to increase in the unchained treatment over the next few yr until available resources diminish (Jessop and Anderson, 2007; Ott et al., 2003; Young and Evans, 1978). We would further predict that annual plant cover in the chained portion of the treatment will not increase, and most likely will decrease over the next decade as maturing perennial grasses continue to use resources. Chaining may also have a direct effect on nonnative annual populations. Depending on biological and physiologic attributes of the species, tillage effects from chaining could bury seeds too deeply in the soil and hinder establishment, or microsites could be created that enhance seedling emergence.

Results from Milford Flat in general provided limited support for our hypotheses. The severity and thickness of the water-repellent layer, while reduced on average, were not significantly different from the unchained plots. However, our measurements of soil $K(h)$ did provide some evidence that the anchor-chaining treatment may have improved soil hydrologic properties, with higher $K(h)$ values in the chained treatment found in the second yr after treatment. On average, anchor chaining increased cover and density of perennial grasses at the Milford Flat fire. While the degree of increase was not found to be statistically significant, having any increase in perennial plants may be biologically significant for the long-term recovery of the site. On arid sites, a seeding is often considered to be successful by land managers if at least 5 plants$\cdot$m^{-2} are established (Lambert, 2005), and this threshold was achieved at the Milford Flat fire.

There may be several reasons why anchor chaining did not provide as great of benefit at the Milford Flat fire as it did at the Cedar Fort fire. It is probable that differences in soil—water repellency and soil texture between the two research locations may have contributed to anchor chaining's treatment response. Particularly during the first 2 yr after the fire, water repellency severity and thickness at the Milford Flat fire were relatively greater than the Cedar Fort fire. The degree of soil—water repellency in a soil is correlated with the proportion of soil particles with a hydrophobic surface coating (Doerr et al., 2006). Because sandy soils have much lower surface area than loamy or clay soils, a greater degree of soil—water repellency can be produced in sandy soils with the same input of hydrophobic compounds (Woche et al., 2005). Coarse-textured soils found at the Milford Flat fire would have also increased aridity of the site through lower water-holding capacity and elevated levels of soil—water repellency, which is generally considered to be most strongly expressed when soils are dry (e.g., Crockford et al., 1991; Dekker and Ritsema, 1994).

Limited improvement in soil hydrologic properties and poor establishment of seeded species at the Milford Flat site may indicate that additional treatments or new approaches are needed to improve the probability of restoration success. One potential approach, which merits further field research, is to coat the seeds with soil surfactant prior to sowing. Madsen et al. (2012b) demonstrated in the laboratory that surfactant seed coating (SSC) technology could increase soil—water infiltration, percolation, and retention within the microsite surrounding the seed, which leads to improved seedling emergence and plant survival. While further field research is needed to verify the efficacy of SSCs, it may be possible that SSC technology could enhance the benefits of the anchor-chaining treatment by further aiding in the reduction of soil—water repellency and improving plant establishment.

While this study demonstrates that anchor chaining may be beneficial, caution should be used as the disturbance from the anchor chain may have negative ramifications. Miller et al. (2012) conducted research at the Milford Flat Fire within the northern end of the fire boundaries. At this location, regional climate and soil-geomorphic factors produce conditions that make the site inherently susceptible to wind erosion. Miller et al. (2012) found in this erosion-prone setting that land treatments, which included the collective use of anchor chaining, drill seeding, and herbicide, exacerbated rather than mitigated wind erosion during the first 3 yr postfire, with their study recording sediment fluxes that ranked among the highest ever recorded in North America.

The study design used for this research focused on those portions of the burned landscape that fell underneath the canopies of burned trees; because of this, results from this study are limited to this microsite and are not directly transferable across the landscape. Despite this limitation in the study design, it can be assumed that areas with high cover of piñon and juniper trees may benefit most from reductions in soil—water repellency through anchor chaining because the canopy area is most susceptible to the development of soil—water repellency (Madsen et al., 2008, 2012a, 2012b, 2012c; Zvirzdin, 2012; Williams et al. 2014). The need for effective postfire restoration treatments that address soil—water repellency issues will increase as piñon-juniper woodlands expand into historically dominant sagebrush/bunchgrass vegetation, increase cover in existing woodland communities, and promote large-scale wildfires. The potential for anchor chaining's ability to decrease soil—water repellency and improve seeding success makes this an increasingly valuable tool for aiding land managers in their postfire seeding efforts of burned piñon-juniper woodlands.

Implications

This is the first field study to provide support for the hypothesis that seeding and anchor chaining can improve soil hydrologic parameters by reducing postfire water repellency levels. Dissipation of soil—water repellency through anchor chaining was associated with increased establishment of perennial grasses from seed, which prevented dominance of the site by cheatgrass and other nonnative annual forbs and grasses. It may be that anchor chaining's ability to improve soil hydrologic properties aided in the establishment of seeded species. However, this study does not definitively indicate this, nor does it show that chaining directly promoted the dissipation of soil—water repellency. Additional research is warranted for understanding the direct impact of anchor chaining on soil—water repellency without the interaction of a seeding treatment.

This study also shows that anchor chaining does not always ensure seeding success. At one site, anchor chaining had limited improvement in soil hydrologic function and establishment of seeded species. These results and similar studies in degraded rangeland systems imply that, while there is a probability that anchor chaining may not improve seeding success, there is also a risk that the site will transition to a nonnative, annual grass-dominated system in the absence of a successful seeding treatment (D'Antonio and Vitousek, 1992; Davies et al., 2011; Ott et al., 2003; Young and Evans, 1978). There continues to be a need to develop and test practices, such as chaining, that have the potential to reduce the risk of seeding failure.

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