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Influence of Soil Water Repellency on Post-fire Revegetation Success and Management Techniques to Improve Establishment of Desired Species

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Techniques to Improve Establishment of Desired Species

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A dissertation submitted to the faculty of
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Doctor of Philosophy

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ABSTRACT

Influence of Soil Water Repellency on Post-fire Revegetation Success and Management

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The influence of soil water repellency (WR) on vegetation recovery after a fire is poorly understood. This dissertation presents strategies to broaden opportunities for enhanced post-fire rangeland restoration and monitoring of burned piñon and juniper (P-J) woodlands by: 1) mapping the extent and severity of critical and subcritical WR, 2) determining the influence of WR on soil ecohydrologic properties and revegetation success, and 3) evaluating the suitability of a wetting agent composed of alkylpolyglycoside-ethylene oxide/propylene oxide block copolymers as a post-fire restoration tool for ameliorating the effects of soil WR and increasing seedling establishment. Results indicate that:

- Post-fire patterns of soil WR were highly correlated to pre-fire P-J woodland canopy structure. Critical soil WR levels occurred under burned tree canopies while sub-critical WR extended out to approximately two times the canopy radius. At sites where critical soil WR was present, infiltration rate, soil moisture, and vegetation cover were significantly less than at non-hydrophobic sites. These parameters were also reduced in soils with subcritical WR relative to non-hydrophobic soils (albeit to a lesser extent). Aerial photography coupled with feature extraction software and geographic information systems (GIS) proved to be an effective tool for mapping P-J cover and density, and for scaling-up field surveys of soil WR to the fire boundary scale.
- Soil WR impairs seed germination and seedling establishment by decreasing soil moisture availability by reducing infiltration, decreasing soil moisture storage capacity, and disconnecting soil surface layers from underlying moisture reserves. Consequently, soil WR appears to be acting as a temporal ecological threshold by impairing establishment of desired species within the first few years after a fire.
- Wetting agents can significantly improve ecohydrologic properties required for plant growth by overcoming soil WR; thus, increasing the amount and duration of available water for seed germination and seedling establishment. Success of this technology appears to be the result of the wetting agent increasing soil moisture amount and availability by 1) improving soil infiltration and water holding capacity; and 2) allowing seedling roots to connect to underling soil moisture reserves.

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Chapter 1: Problem Statement

The pronounced expansion of woody vegetation in semi-arid ecosystems has been observed globally (Briggs et al., 2002; Huxman et al., 2005; Breshears, 2006). Primary causal factors include high intensity grazing, fire suppression (Bragg and Hulbert, 1976; Heisler et al., 2003), increased atmospheric CO_2 concentrations (Mayeux et al. 1991; Johnson et al. 1993), and climate change (West, 1999; Miller and Tausch, 2001; Romme et al., 2009). In the Western United States, the range of expansion and stand infilling by piñon (*Pinus*) and juniper (*Juniperus*) (P-J) species into grassland and sagebrush communities constitutes one of the greatest afforestations of our time (Miller et al., 2008). Since European settlement of the Western United States, these species have expanded their range to more than 40 million hectares (Romme et al., 2009). This ecosystem shift has resulted in negative impacts to soil resources, plant community structure and composition, forage quality and quantity, water and nutrient cycles, wildlife habitat, and biodiversity (Miller et al., 2008). As P-J woodlands mature, increased fuel loads and canopy cover can lead to large scale, high intensity crown-fires (Miller and Tausch, 2001; Miller et al., 2008). After a fire, the ability of a P-J dominated ecosystem to recover depends on the extent to which physical and biological processes controlling ecosystem function have been altered (Briske et al., 2005, Miller and Tausch, 2001). When ecological thresholds are crossed in these systems, the recovery of desirable species may not be possible without affective restoration treatments. Areas associated with P-J vegetation often remain bare for one or more years after fire (Fig. 1). If desirable species do not establish sufficiently to utilize available resources in the first couple of years following a fire, sites can transition into a secondary state of weed dominance, which then promotes more frequent fire return intervals and decreases native plant establishment, further impairing vital ecosystem functions (Young and Evans, 1978; Wisdom et al., 2003) (Fig. 1).

One factor that can restore natural processes and prevent threshold transitions is the successful establishment of desirable vegetation within the first year after a fire. In the past, land managers have typically selected introduced species for post-fire rehabilitation. These species, such as crested wheatgrass (*Agropyron cristatum* (L.) Gaertn) and forage kochia (*Kochia prostrate* (L.) Schrad), often have more consistent establishment, are inexpensive, can compete against weeds, and are highly valued as forage for livestock. Currently, fire rehab programs are increasing the use of native plant materials in place of introduced species in an effort to reinstate ecosystem processes and improve species diversity after a fire; however, these species are costly and establishment success is typically less than desirable (Roundy et al., 1997). Therefore, the use of native species in post-fire restoration increases project costs while decreasing the chance of successfully establishing a weed-resistant community. When restoration practices fail, ecological resilience is compromised, and soil loss, weed invasion, and other factors function as triggers, initiating feedback shifts that carry a site across ecological thresholds to undesirable alternate stable states. Land management personnel in the Intermountain West are calling for researchers to develop new techniques to improve establishment of native plant materials in order to restore habitats lost to wildfire and subsequent dominance by cheatgrass *(Bromus tectorum* L.*)* and other weeds.

In order to develop successful post-fire restoration approaches, it is critical that we understand both the mechanisms that impair vegetation recovery after a fire and the conditions that developed prior to the fire that resulted in the crossing of ecological thresholds. If the state of an individual site is known in relation to ecological thresholds and possible transitions to other states, capital can be correctly allocated to sites in transition, in order to promote the system's natural ability for self-repair. Furthermore, an understanding of the mechanisms that prevent post-fire recovery will allow the development of resilience-based approaches that promote recovery of post-fire ecosystem process and function (Briske et al. 2005).

Woody vegetation in general has been shown to create more favorable conditions for their own survival by modifying several soil hydrological and biogeochemical properties, (Charley and West, 1975; Barth and Klemmedson, 1978; Lebron et al., 2007; Madsen et al., 2008; Ravi and D'Odorico, 2009). Modification of the soil through the development of a water repellent layer has been hypothesized to be ecologically advantageous for the survival of woody vegetation in arid environments (Scott, 1992; Moore and Blackwell, 1998; Jaramillo et al., 2000; Madsen et al., 2008). In unburned systems, organic compounds, primarily aliphatic hydrocarbons, are believed to be the cause of soil water repellency (Doerr et al., 2000). These compounds can originate from several sources, including plant litter material, microbial activity, and fungal hyphae (Jaramillo et al., 2000; Doerr et al., 2000). Madsen et al. (2008) observed that during precipitation events, thick litter mounds helped retain soil moisture from running off site, while the hydrophobic soil channeled precipitation inputs towards breaks within the hydrophobic layer where it could then be transferred deeper into the soil profile. This transfer of moisture may be ecologically advantageous for established woody plants in arid environments by minimizing evaporative losses from the soil surface.

While soil water repellency may be a water conservation mechanism for established woody species, we hypothesize that it may also act as a temporal ecological threshold by impairing establishment of desired species within the first few years after a fire, which then leaves resources available for weed invasion once water repellency has diminished. In general, during a fire, heat vaporizes hydrophobic compounds, along with organic substances from the litter and upper soil layer. When the molecular weight of these molecules is greater than the surrounding air, they move downward and condense within the cool underlying soil layers, coating soil particles (Savage et al., 1974; Doerr et al., 2000; Letey, 2001). The resultant soil profile consists of a shallow wettable layer at the surface and a potentially intensified zone of water repellent soil below the surface, which can be more than several centimeters thick (DeBano 2000; Savage, 1974; Doerr et al., 2000; Letey, 2001) (Fig. 2). The development or enhancement of a water repellent layer just below the soil surface may result in a zone with limited available soil moisture. Lower soil moisture content in this zone can decrease seed germination and increase seedling mortality. In conjunction with reseeding efforts, decreased establishment of desired species within the first few years after a fire may leave resources available for weed invasion once water repellency is diminished.

For shrublands invaded by P-J woodlands (Romme et al. 2009), soil water repellency's occurrence, severity, persistence, and spatial distribution may be a function of tree cover. Currently, woodlands are not only increasing in age and size, but also experiencing accelerated rates of canopy infilling. This has been attributed to elevated atmospheric CO_2 concentrations facilitating improved P-J water use efficiency (Johnson et al. 1993; Knapp and Soulé 1996; Miller and Tausch, 2001).We hypothesize that woodlands with higher and more contiguous P-J cover will have a greater area affected by water repellency, as compared to areas with lower P-J cover. At the landscape scale we expect post-fire recovery thresholds to be crossed as pre-fire canopy infilling increases the continuity of soil water repellency (i.e. sites transition from individual trees to closed canopy forest). These thresholds are expected to be most closely related to a loss of soil quality and increased weed dominance. Loss of soil quality often triggers feedback shifts that carry sites across ecological thresholds. Any increase in soil water repellency extent across a landscape has the potential to decrease infiltration capacity and soil stability of a watershed, leading to direct increases in soil erosion by wind and water (Ravi et al., 2006; Woods et al., 2007). In light of the hypothesized relationship between the breakdown of water repellency and site recovery, processed-based models that predict the extent and potential impacts of soil water repellency on revegetation will help guide land managers in their post-fire restoration efforts. Furthermore, these models will predict potential future impacts associated with climate change, increased stand age, and canopy closure.

Restoration approaches which focus on ameliorating water repellency could potentially improve the success of native plant materials in post-fire reseeding efforts while simultaneously decreasing runoff and soil erosion, and preventing weed domination. Use of commercially available surface wetting agents (or surfactants) may provide an alternative post-fire restoration approach where water repellency inhibits site recovery. Wetting agents are generally organic molecules that are amphiphilic (hydrophobic tails and hydrophilic heads). Wetting agents reduce surface tension of water by adsorbing at the liquid-gas interface. A wide variety of ionic and nonionic wetting agents are produced commercially, ranging from simple dish soaps to sophisticated polymers chemically engineered to overcome water repellency. In the case of soil applications, the hydrophobic tail of the wetting agent chemically bonds to the non-polar hydrophobic coating on the soil particle; while the hydrophilic head of the molecule attracts water molecules.

Various small plot, post-fire research projects located in the mountains of southern California have shown that the application of wetting agents after a fire can reduce soil erosion and improve vegetation establishment (e.g. Osborn et al., 1964; Pelishek et al., 1964; Osborn et al. 1964; Krammes and Osborn, 1969; Debano, 2000). These studies suggest that wetting agent applications can be a successful post-fire treatment. While wetting agents have not been used in wildland systems since the 1970's, they have been extensively used and further developed within various aspects of the agricultural industry, with most applications in turfgrass systems (e.g. Cisar et al., 2000; Kostka, 2000. Subsequently, the effectiveness of these chemicals in overcoming soil water repellency has been improved (Cisar et al., 2000; Kostka, 2000; Kostka and Bially, 2005). The development of these wetting agents may provide an innovative approach for alleviating the effects of water repellency on germination and establishment of native vegetation species, thus allowing reseeded species to better compete with invasive annual weed species such as cheatgrass.

This dissertation presents strategies to broaden opportunities for enhanced post-fire rangeland monitoring and restoration of burned P-J woodlands by: 1) developing methodologies for mapping the extent and severity of critical and subcritical water repellency, 2) determining the influence of water repellency on soil ecohydrologic properties and revegetation success, and 3) evaluating the suitability of a wetting agent composed of alkylpolyglycoside-ethylene oxide/propylene oxide block copolymers as a post-fire restoration tool for ameliorating the effects of soil water repellency, and increasing seedling establishment.

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FIGURES

Fig. 1 A. Late season photo of a juniper tree one year after the fire; despite reseeding efforts, the soil in the subcanopy region is bare of vegetation, and the annual weed cheatgrass *(Bromus tectorum)* is starting to establish on the edge of the subcanopy; perennial grasses are growing outside the influence of the tree. **B**. This same burned tree, in spring, two years post-fire; note how the subcanopy area is cheatgrass dominated (senesced vegetation), while the intercanopy exhibits substantial perennial cover (live vegetation).

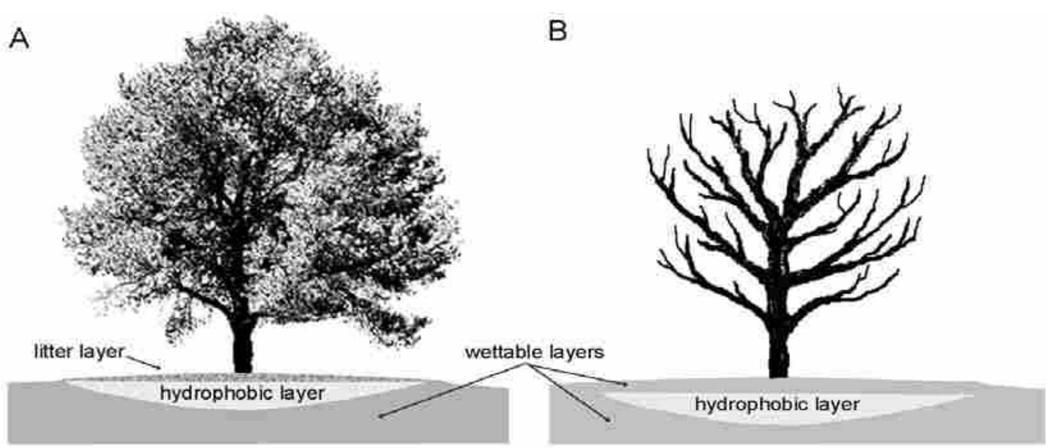

Fig. 2 A. In unburned juniper systems, soil water repellency is present in the litter duff and upper mineral soil layers. **B.** Heat volatilizes organic substances, which then move downward and condense within the cool underlying soil layers, often forming a more impenetrable water repellent layer just below the soil surface (Modified from Madsen et al., 2008).

Chapter 2: Development of Feature Extraction Techniques for Estimating Piñon and Juniper Tree Cover and Density and Comparison with Field Based Management Surveys

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Summary

1. In Western North America, expansion and stand infilling by piñon (*Pinus*) and juniper (*Juniperus*) (P-J) trees constitutes one of the greatest afforestations of our time. Feature extracted data acquired from remotely sensed imagery can help managers rapidly and accurately assess this expansion at broad landscape-scales.
2. The objectives of this study were to 1) develop an effective and efficient method for accurately quantifying P-J tree canopy cover and density directly from high resolution photographs; and 2) compare feature extracted data to typical in-situ datasets used by land managers.
3. Tree cover was extracted from 25 cm resolution aerial-photography using Feature Analyst®, an extension for ArcGIS 9.3. Tree density was calculated as the sum of the total number of individual polygons (trees) within the feature cover class after isolation using a negative buffer post-processing technique.
4. Feature extracted data were compared to ground reference measurements and existing statewide estimates collected through the line intercept and point quarter methods, respectively, by the Utah Division of Wildlife Resources Range Trend Project (DWR-RTP).
5. Results indicate that the proposed feature extraction techniques for cover and density are highly correlated to ground reference and DWR-RTP measurements. Estimates of cover generally showed a near 1:1 relationship to ground reference and DWR-RTP, while tree density was underestimated; however, after calibration a near 1:1 relationship and significant correlation were realized.
6. *Synthesis and applications*. Feature extraction techniques used in this study provide an efficient method for assessing important rangeland indicators, including: density, cover, and extent of P-J tree encroachment. Additionally, correlations found between field and feature extracted data provide evidence to support extrapolation between the two approaches when assessing rangeland status.

Keywords: aerial photography, geographic information systems (GIS), remote sensing, piñon and juniper tree encroachment, rangeland monitoring,

Introduction

The pronounced expansion of woody vegetation in semi-arid ecosystems has been observed globally (Briggs, Knapp & Brock 2002; Huxman et al. 2005; Breshears 2006). Primary causal factors include high intensity grazing, fire suppression (Bragg & Hulbert 1976), increased atmospheric CO_2 concentrations (Mayeux, Johnson & Polley 1991; Johnson, Polley & Mayeux 1993), and climate change (Miller & Tausch 2001; Romme et al. 2009). In the western United States, the range of expansion and stand infilling by piñon (*Pinus*) and juniper (*Juniperus*) (P-J) species constitutes one of the greatest afforestations of our time (Miller et al. 2008). Since European settlement of the western United States these species have expanded their range to more than 40 million ha (Romme et al. 2009). Expansion of these woodlands into other ecosystems can result in negative impacts to natural fire regimes, soil resources, plant community structure and composition, forage quality and quantity, water and nutrient cycles, wildlife habitat, and biodiversity (Miller et al. 2008).While degradation is site dependent (Miller & Tausch 2001), P-J canopy cover and density can be important indicators of the degree that encroachment is controlling physical and biological processes (Miller et al. 2005; Miller et al. 2008). Consequently, land managers are actively involved in monitoring these parameters to develop appropriate management plans.

In Utah, the Division of Wildlife Resources Range Trend Project (DWR-RTP) has collected rangeland trend data across the state of Utah since 1983 (Summers et al. 2007). The DWR-RTP uses the line-intercept and point quarter methods to estimate tree cover and density, respectively (Summers et al. 2007). However, due to the heterogeneity of rangeland systems it is difficult to extrapolate these data beyond the area where the measurements were made.

Additionally, rangeland areas are generally extensive and inaccessible. Consequently, monitoring such large areas through field methods alone is not economically possible (Hunt et al. 2003).

With the recent availability of remote sensing sensors and platforms that can measure canopy reflectance at resolutions finer than individual trees, tree canopy cover can be effectively characterized over large land areas (Hunt et al. 2003). Feature extraction (FE) techniques for classifying tree cover using high resolution panchromatic and multispectral data have been proposed by several authors (i.e. Hunt et al. 2003; Afinowicz et al. 2005; Petersen, Stringham & Laliberte 2005; Weisberg, Lingua & Pillai 2007). These methods use highly effective software that can incorporate spatial, textural, and spectral information from remotely sensed imagery to segment tree cover from the surrounding landscape. However, research is currently lacking that quantifies the degree of correlation between field-based measurements and FE data. Both are not absolute and consequently are subject to error and bias. Accuracy assessments are commonly used to verify the reliability of FE data, by comparing with field-based observations at the same geographic location. While this approach verifies the accuracy of the model, it does not quantify how these values relate to estimates derived from typical field-based techniques.

Research is also needed to explore more accurate and efficient ways to assess P-J woodland encroachment. Estimates of cover have received a significant amount of attention (i.e. Weisberg, Lingua & Pillai 2007), but methods for estimating density are lacking. Density is typically estimated empirically through correlations between field plot measurements and cover values extracted from remotely sensed imagery. This approach can be labor intensive and inaccurate, due to the field work required for calibration with the imagery and loss of accuracy beyond field plot calibration locations if variances in the cover-density relationship exist (i.e. if average canopy size changes). This variation has the potential to render this method ineffective to managers seeking to use tree density as an indicator of encroachment. Therefore, it would be advantageous to develop feature extraction techniques that could extract tree density directly from remotely sensed imagery.

The primary objectives of this study were to: 1) develop an efficient method for accurately quantifying P-J tree canopy cover and density directly from high resolution aerial photographs; and 2) compare FE data to typical in-situ datasets used by land managers in assessing rangeland health. Results of this study have important applications in monitoring P-J woodland encroachment, fuel loads, biomass energy potential, and rangeland health (Tausch et al. 2009).

Materials and Methods

Study locations and in-situ methods for estimating cover and density

Statewide in-situ data collected by the DWR-RTP was selected for comparison with FE data because of its large spatial distribution of study sites, reliability, and repeated use in land management policy and decision making (Summers et al. 2007). At the time of the study the DWR-RTP was monitoring 838 sites throughout Utah, 287 of which contained P-J vegetation. In Utah, P-J woodlands consist predominantly of Utah juniper (*Juniperus osteosperma* (Torr.) Little), occurring either alone or together with singleleaf piñon (*Pinus monophylla* Torr. & Frém.) (West 1989) or twoneedle piñon (*Pinus edulis* Engelm). Some of the other less common trees/tall shrubs that can be found in P-J woodlands on these sites include Gambel oak (*Quercus gambelii* Nutt.), Sonoran scrub oak (*Quercus turbinella* Greene), bigtooth maple (*Acer grandidentatum* Nutt.), curl-leaf mountain mahogany (Cercocarpus ledifolius Nutt.), true mountain mahogany (*Cercocarpus montanus* Raf.), and antelope bitterbrush (*Purshia tridentata* (Pursh) DC). The most dominant understory shrub across all sites is big sagebrush (*Artemisia tridentata* Nutt.), various subspecies of which are distributed across the state. Dominant grass species also vary across the state, with cool season bunchgrasses common in the northwest and warm season sod grasses in the southeast (West 1989).

For comparison of FE data with DWR-RTP methods, 35 sites were selected based on imagery availability, piñon or juniper presence, absence of tree control treatments, and timing of field measurements (plots were selected that had been measured between 2004-2008) (Fig. 1). Cover and density were measured at each site by the DWR-RTP along five 30.5 m belt transects were centered perpendicular to a 152.4 m baseline transect at 3.4, 40.8, 78.9, 113.1, and 150.9 m (Summers et al. 2007) (Fig. 2A). Canopy cover was measured along the 30.5 m belt transects with the line-intercept method, with percent cover equal to the length intersected by trees, divided by the total length (Summers et al., 2007). At the intersections of the baseline transect and the five belt transects, tree density was determined using the point quarter method (Cottam & Curtis 1956). Individual trees were additionally classified by height as follows: C1, <30cm; C2, 30-122cm; C3, 122-244cm; C4, 244-366cm; and C5, >366cm.

Image processing

Flow diagram of the feature extraction process to derive tree cover and density is shown in Fig. 3. Feature extraction was performed on 25cm High Resolution Orthophotography (HRO), color (RGB) aerial-photographs obtained from the Utah Automated Geographic Reference Center (AGRC), projected in Universal Transverse Mercator (UTM) coordinates, Zone 12 NAD83 datum (AGRC, 2008). Photographs were taken in the fall (October-November) of 2006. Imagery obtained during this period was particularly valuable for this study because the evergreen P-J vegetation was easily differentiated from seasonally-dormant vegetation.

At each DWR-RTP study site, tree cover and density were remotely measured within a 75.0 m buffer area surrounding the DWR-RTP 152.4m base-line transect. We used an area larger than the area measured in the field by the DWR-RTP to demonstrate the ability of the feature extraction methods to extract vegetation data over large land areas. Comparisons between the measurements were performed within the area directly measured by the DWR-RTP, which we estimated to be a 15.3m buffer area surrounding the DWR-RTP base-line transect, with 15.3m being the distance belt transects were extended from the baseline transect.

Feature extraction (cover)

Tree cover of P-J vegetation was extracted from the imagery using the Feature Analyst software extension (Visual Learning System's Inc., 2002) for ArcGIS® 9.3 (Fig. 2A). Training for the Feature Analyst classifier is performed by providing input in the form of digitized polygons that representative of P-J tree cover, or non-P-J features (e.g. bare ground, non-P-J vegetation, etc.). Training sets for these two classes are then combined into one multi-class input layer, and the software then extracts features representing these two classes using several custom feature extraction options, which are a part of the Feature Analyst "Set Up Learning" dialog box. We experimented with several of the extraction options associated with the learner. Based on best visual assessment, we concluded that a pre-defined foveal pattern of nine cells was the most accurate search pattern for P-J canopy extraction, for this type of imagery. Images were modeled by drawing a minimum of 10 P-J training sets. An additional set of 10 or more training sets was provided if images contained vegetation types with brightness values similar to P-J vegetation.

Following the initial extraction, we used various hierarchical learning tools (i.e. removing clutter, adding missed features) to modify the output file until the feature class was a visually accurate representation of tree canopy cover. Cover was calculated by dividing the classified tree canopy area by the total land area within the plot.

Feature extraction (density)

Within all DWR-RTP sites there were locations where the canopy of individual trees either touched or appear to be touching other trees. Consequently, single polygons often represented more than one tree, preventing us from directly extracting density (Fig. 2C). To resolve this problem, we initially applied a negative buffer technique to each output file that separated polygons representing multiple trees into subsets representing individual trees. Unfortunately, this method also eliminated low-area polygons representing smaller trees. To circumvent this: 1) polygons were ranked by area and two categories were created, one with low-area polygons representing single trees and the other with high-area polygons representing multiple trees, and 2) a negative buffer was applied to the high-area polygons, breaking them out into smaller polygons representing individual trees. Following the application of the negative buffer, if some individual polygons still represented more than on tree, these steps were repeated. The dividing point between the two categories was determined by visually selecting polygons in ascending order, based on area, until polygons representing more than one tree began to be selected. This separation point between low and high area polygons was variable from image to image. Different sizes of negative buffers were applied to each cover output file until an optimal buffer distance was identified that most accurately separated polygons, such that individual trees were represented (Fig. 2C). Density was calculated as the total number of polygons within the plot.

Accuracy assessment

Several approaches were used to assess the accuracy of the DWR-RTP and feature extraction data. The first approach assessed the on-screen accuracy of the produced thematic cover maps through random point generation, to determine if additional post-processing was required. Classified images that had an overall accuracy of less than 90% were subjected to additional post-processing, until 90% or greater accuracy was achieved. On screen accuracy assessment of cover was performed for each site using ERDAS Imagine 9.1 (ERDAS Inc., Atlanta, GA). For each class (P-J canopy or non-P-J features) 35 random points were generated, with sample size calculated directly from a binomial distribution, with a 95% confidence level and acceptable error of 10% (Jensen 2005). This approach produced a total of 70 validation points per site and 2,520 points in the study (35 points per class × two classes × 36 sites = 2,520 points). Assessment of on-screen accuracy for tree density was performed by comparing the total number of trees visually detected by to the number identified through feature extraction.

In-situ accuracy assessments of tree cover, as estimated by the DWR-RTP and FE techniques, were conducted on seven randomly selected DWR-RTP sites within a 110 mile radius of Provo, UT (Fig. 1). Two separate in-situ approaches were used for evaluating cover. The first approach assessed FE techniques through random point generation. In this approach 35 random points per class were downloaded onto a handheld Trimble GeoXH global positioning system (GPS) receiver (Trimble, Sunnyvale, CA) and validated for accuracy in the field. This approach produced a total of 70 validation points per site and 490 points for the study (35 points per class × 2 classes × 7 sites = 490 points).

While the standard accuracy assessment methods performed above in conjunction with ERDAS Imagine evaluated the accuracy of the produced thematic map in distinguishing trees from other features, its relationship to actual tree cover and density is indirectly assumed. The second in-situ approach for assessing accuracy provided a direct correlation between estimates of FE and DWR-RTP data with actual on the ground tree cover and density. Ground reference (GR) of canopy cover data was estimated by measuring the total area of all tree canopies within the plot using the crown-diameter method (Mueller-Dombois & Ellenberg 1974). Ground reference of tree density was obtained by counting each tree within the plot and recording its respective height.

To better understand the sources of error associated with feature extraction techniques in this study, a GPS point was taken for each tree in the plot and its position relative to other trees was noted. In the laboratory, GPS points that correlated with a tree on the produced thematic tree density map were marked as extracted. Trees not extracted were grouped into one of four categories based on the possible reasons for the lack of extraction, including: 1) trees that were underneath larger trees; 2) trees that formed conglomerates with other trees; 3) trees in close proximity to other trees (i.e. trees in close proximity that appeared to be touching as a result of shadow or blending of pixels); and 4) trees below the detection limit (i.e. trees below a specific size).

Statistical analysis

Error matrix tables showing classification accuracy, species-level producers and user's accuracy, and kappa statistic were generated from the on-screen and in-situ classification of the random points generated in ERDAS Imagine (Congalton 1991). Comparisons of tree cover and density values were made between GR, FE, and DWR-RTP data collected from the seven randomly-selected DWR-RTP sites used to assess accuracy assessment. Comparisons of tree cover and density were also made between FE and DWR-RTP data for all plots in the study. Tree density comparisons were also made between calibrated FE data and DWR-RTP data. Two different approaches were tested for calibrating FE density. The first approach calibrated FE density by adding the average number of unextracted trees to the original FE density at each of the seven sites, according to the equation 1:

Eqn. 1. $\text{FE (cal.)} = \frac{\text{FE}}{1 - d/100}$

where *d* is equal to the percent of the GR trees not detected by FE techniques. The second approach calibrated FE density using the trend-line developed between GR and FE density, according to equation 2:

Eqn. 2. $\text{FE (cal.)} = (\alpha * \text{FE}) + \beta$

where α is equal to the slope and β is the y intercept.

Statistical analysis of the measurement approaches was performed using Sigma Stat 3.1 (Systat Software, Inc. Richmond, CA). For all comparisons a significance level of $P < 0.05$ was used. Datasets were found to be normally distributed by the Kolmogorov–Smirnov test. Comparisons were made using linear regression and summary statistics (mean, standard error, range, and relative percent difference). Differences between mean values were determined through a paired t-test; while differences between mean relative percent difference values was assessed through a two-sample t-test. Relative percent difference was calculated according to Eq. 3:

Eqn. 3. Relative percent difference = $\frac{|x_1 - x_2|}{(x_1 + x_2)/2} \times 100$

where the absolute difference of two measurement approaches (x_1 and x_2) is divided by their mean, and multiplied by 100. The smaller the relative percent difference, the more accurate the method is assumed to be when compared to ground truth data. When making comparisons between the DWR-RTP and FE data the smaller the number the higher the correlation.

For clearly discernable individual trees (i.e. we did not include trees underneath larger trees, in conglomeration with other trees, or proximal to other trees) logistic regression was used to determine the 95% probability of detection for tree canopy area, width, and height (Hosmer & Lemeshow 1989) according to equation 4:

Eqn. 4. Probability of detection = $\left(\frac{P_z}{\mathbf{1} - P_z}\right) = \beta_{\mathbf{1}} + \beta_2 * x$

where β_1 and β_2 are probability variables derived from logistic regression analysis, P_z is the probability of occurrence, with ln (P_z/ (1-P_z) representing the odds ratio linearized through the logit transformation, x equals average canopy width, canopy area or canopy height.

As land management field-based surveys often correlate tree height with various ecological parameters, such as tree age, fuel loads and woodland encroachment phase (e.g. Bradshaw & Reveal 1943; Miller, Meeuwig & Budy 1981; Dixon 2003; Tausch et al. 2009;

Summers et al. 2007), we determined the correlation between canopy width, area and tree height, to correlate feature extracted data with field based surveys that record only height.

Results

Random point generation accuracy assessment

Tree cover estimated through FE values were found to be highly accurate, as verified with both on-screen and in-situ random point generation accuracy assessments. On-screen and in-situ RPG assessments had overall accuracies of 95.1 and 93.1%, and Kappa statistics of 0.90 and 0.86, respectively (Table 1). User's accuracy and producer's accuracy were similar, indicating an equal number of omission and commission errors (Table 1).

Ground reference accuracy assessment of tree cover

Liner regression analysis results are given in Fig. 4. A high correlation was found between GR vs. FE cover ($r = 0.99$, $P < 0.001$), with a near 1:1 relationship ($\alpha = 1.01$), and y intercept near zero ($\beta = 0.768$). Tree cover measured by the DWR-RTP was not as strongly correlated to GR data ($r = 0.75$, $P = 0.053$); the y intercept was near zero, but the slope of the regression line was greater than one, indicating an underestimation of tree cover on sites with higher cover values ($\alpha = 1.15$, $\beta = 0.29$).

Table 2 compares summary statistics and percent differences between GR, FE, and DWR-RTP data, for accuracy assessment sites. Summary statistics were similar between the measurement approaches, with mean cover values of 15.0±3.4%, 14.1±3.3%, and 12.8±2.2% for GR, FE, and DWR-RTP, respectively. Average percent difference between GR vs. FE cover was

11.0±3.4%; average percent difference between DWR-RTP vs. GR cover was statistically higher, 29.9±6.3% (P = 0.021) (Table 2).

Ground reference accuracy assessment of tree density

Regression analysis showed a high correlation between GR vs. FE density (r = 0.96, P < 0.001) (Fig. 4). With the exception of one low density site, FE data consistently underestimated tree density (α= 1.73, β = -21.9). Tree density measured by the DWR-RTP through the point-quarter method was also highly correlated to GR data (r = 0.95, P = 0.001), with a near 1:1 relationship between the measurements (α= 1.15, β = 29.0).

Mean GR density was 214.8 trees ha^{-1}, while FE density was statistically lower, with 137.0 trees ha^{-1}. DWR-RTP density was similar to GR density with 203.2 trees ha^{-1}. Analysis of the percent difference between GR vs. FE, and GR vs. DWR-RTP showed no significant differences between the two comparisons (P = 0.287). The mean percent differences for GR vs. FE, GR vs. DWR-RTP, and FE vs. DWR-RTP were 38.1±6.9, 24.6±10.0, and 45.0±8.6%, respectably.

Source of error Analysis

Table 3 shows the types of trees FE methods were unable extract. The majority of the trees not extracted for both cover and density were below the minimum detection limit size. These trees had no significant influence on overall cover, comprising only 1.0% of the total GR tree cover. Conversely, analysis of density showed 38.7% of the trees were not detected, with 23.8% below the detection limit, 9.1% underneath larger trees, 4.5% in close proximity, and1.3% in conglomerate with other trees.

Fig. 5 illustrates the results of logistic regression models showing the probability of tree extraction based off of tree height, mean canopy width, or canopy area. Canopy area and tree width were the strongest predictor variables ($P < 0.001$ for both variables), as illustrated by the quick transition from almost no trees being detected to 95% or more of the trees detected. The 95 % probability of detection for canopy area and average tree width are 2.0m^2 and 1.4m, respectively. With respect to canopy area, based on the 25cm resolution imagery used in this study, trees would need to encompass 32 pixels or more to be consistently extracted from the imagery. Tree height was also a significant predictive variable for tree extraction ($P < 0.001$). The 95% probability of detection for tree height was 2.6m (Fig. 5). The ability of tree height to be used as a predictive variable is probably due to the covariant relationship between canopy area or width and tree height. From our data set there was a strong correlation between tree height and average canopy width, and for tree height and canopy area (Fig. 6).

Comparison of feature extracted and DWR-RTP data (global dataset)

Regression analysis between FE and DWR-RTP cover for all sites analyzed in the study is shown in Fig. 7. Results indicate a high correlation between the two measurement approaches ($r = 0.96$, $P < 0.001$, $\alpha = 0.92$, $\beta = 1.14$) (Fig. 7). Table 4 compares summary statistics and the percent difference between FE and DWR-RTP cover. Comparison of summary statistics shows that the two approaches are quite similar. Average FE and DWR-RTP cover was estimated to be 14.3±2.1 and 14.1±2.2%, respectively. Average percent difference between the two sites was 44.3±8.9%.

Regression analyses of tree density showed significant correlation between FE and DWR-RTP methods ($r = 0.83$, $P < 0.001$), with the majority of FE data points underestimating tree density (α= 1.6, β = 21.5) (Fig. 7). Calibration of FE data with Eq. 1, produced a similar correlation (r = 0.83, $P < 0.001$) with a near 1:1 relationship (α= 0.96, β = 31.5) (Table 4). Calibration of FE with Eq. 2 produced the same correlation (r = 0.83, $P < 0.001$), and a similar near 1:1 relationship (α= 0.90, β = 41.3). Following the application of either equation, FE underestimated density at low tree densities and slightly overestimated at high tree densities, though the effect was greater with Eq. 2.

Summary statistics show that on average FE techniques significantly underestimate tree density as compared to DWR-RTP methods (P = 0.013), averaging 149.3±18.6 and 254.9±34.9 trees ha^{-1}, respectively (Table 4). Calibration of FE data with Eq.1 and Eq. 2 increased the average density to 243.5±30.3 and 236.4±32.8 trees ha^{-1}, respectively, which are statistically similar to DWR-RTP (P = 0.807 and 0.698, respectively). The average relative percent difference between FE and DWR-RTP density was 53.9±7.6 % (Table 4). While not significant, calibration of FE data with Eq. 1 and Eq. 2 decreased the relative percent difference to 44.8±8.4 % and 40.6±5.9 %, respectively (P = 0.174 and 0.427, respectively).

Discussion

Accuracy of feature extracted data

Accuracy assessment of the produced thematic maps by random point generation demonstrated the ability of Feature Analyst extraction software to distinguish P-J canopy cover from various other attributes such as bare-ground, shrubs, grassland vegetation, and shadow (Table 1). These results are consistent with similar studies that use FE software to determine woody vegetation coverage from aerial photography (i.e. Anderson & Cobb 2004; Afinowicz et al. 2005; Petersen et al. 2005; Weisberg et al. 2007; Smith et al. 2008).

The relationship found between FE tree cover and GR measurements is also consistent with previous studies (i.e. Anderson & Cobb 2004). Results show that when FE data is compared to GR data there is a near 1:1 relationship (Fig. 4), similar average values and relative percent difference, (Table 2). Based on these results we postulate that the imagery used in this study (25 cm) is ideal for acquiring FE tree cover. We do not anticipate that higher resolution imagery will produce results significantly more accurate than those obtained in this study (Table 3).

Our method for extracting P-J tree density from produced thematic cover maps, using a negative buffer post-processing technique, is unique to this study. Results indicate this approach is highly correlated to GR data, but consistently underestimates tree density. As illustrated in Table 3, the highest source of error involved trees below the detection limit, with 23.8 % of the total GR trees sampled below this point. In this study, tree area was the best predictor of tree extraction; the minimum tree area required for consistent tree extraction (95% probability) was 2.0 m^2 (Fig. 5). Regression analysis from the data collected in this study (Fig. 6) would predict trees of this area to be 2.1 m tall. Based on typical P-J tree classifications by Bradshaw and Reveal (1943), out of four classes (i.e. Class 1- reproduction (seedlings and saplings), tree height <1.4 m; Class 2- immature, tree height 1.4-4.3 m; Class 3- mature, tree height 3.0-9.1 m; and Class 4- overmature, tree height >3.7 m), FE techniques are able to extract all but Class 1 trees.

The remaining sources of error include: trees proximal to other trees, trees forming conglomerates, and trees underneath larger trees. The nature of the latter two precludes extraction regardless of the imagery resolution. We predict that if resolution were increased to 0.0347 m, all but seedlings (defined by the DWR-RTP as trees below 30 cm) and unextractable trees (i.e. trees forming conglomerates and trees underneath larger trees) could be extracted. Rational for the development of this number is based on the assumption that the relationship between the image resolution used and the size of the trees extracted remains constant. If this relationship holds true, the imagery resolution required to extract a 30 cm tall tree, would be equal to the area of this tree (0.0385 m^2, based on the tree height-canopy area correlation developed previously) divided by the minimum number of pixels required to realize a 95% probability of extraction using the FE techniques established in this study (32 pixels), this equation yields 0.0347 (0.0385 m^2 / 32 = 0.001203 m^2, $\sqrt{0.001203\ m^2}$ = 0.0347 m). However, it is important to acknowledge, as with this study and others, several factors can influence the quality of the aerial photography and subsequent tree sizes detected. Motion blur, tree shadow, color aberrations, atmospheric variability, georectification, as well as methods and instrumentation used in acquiring the images can all influence image quality (Booth & Cox 2006; Booth et al. 2008; Moffet 2009).

Accuracy of DWR-RTP data

Unlike FE techniques, accuracy assessment results appeared to show that the DWR-RTP methods were not significantly correlated with tree cover. However, it is important to note that the *P* value was just above the significance threshold. Lack of significance in this data set can be explained in part due to one sample point beyond the 95% confidence interval. After the removal of this point a significant correlation was found ($r = 0.87$, $P = 0.025$), with the trend line just off of the 1:1 line ($\alpha = 0.98$, $\beta = 0.48$). Further examination of the outlier site showed that the randomly-placed line transects missed the majority of the trees in the plot. This error was not found in the FE data because these data are less affected by the number of plants or their patchiness. Furthermore, analysis based on relative percent error indicates that FE techniques are a more accurate estimate of tree cover as compared to the DWR-RTP. Even after the removal of the outlier point the percent difference between GR vs. DWR-RTP remained statistically higher than GR vs. FE (P = 0.048), with percent differences of 24.6±4.1 and 12.3±3.7%, respectively (compare with Table 2).

DWR-RTP tree density was highly correlated to GR data, but did not show as high of correlation as was found between GR vs. FE density. However, unlike FE density, the DWR-RTP data exhibited a near 1:1 relationship to GR data because of its ability to extract juvenile trees (Fig. 4). This is a major benefit of the DWR-RTP methods that has important implications for rangeland management. For example, early detection of tree encroachment is important because it enables proactive treatments to occur (i.e. controlled burns) before ecological thresholds are crossed (i.e. Miller et al. 2005). Understanding the density of juvenile trees is also important when determining if a site is suitable for mechanical treatment. Sites that have an established population of mature trees but also have a number of seedlings may have short-lived response to mechanical treatment. For example "green chaining" of P-J woodlands by pulling a large anchor chain between two bulldozers, is an effective method for the removal of mature trees, but tends to pass over limber seedlings and saplings. If there is a high population of seedling or saplings on site, benefits from green chaining treatments may be short-lived because the larger trees will quickly be replaced by the young trees not removed by the chaining treatment.

DWR-RTP vs. feature extraction methods (global data)

The fact that FE data was highly correlated with GR accuracy assessment and DWR-RTP global cover data (Fig. 7), verifies that the one outlier point significantly contributed to the poor correlation found between the DWR-RTP and GR comparison (Fig. 4). This same outlier was also well beyond the 95 % confidence interval in the comparison between FE and DWR-RTP global datasets for cover Fig. 7. Comparison of the two global datasets shows that the two approaches are comparable, with slight differences that we suspect, based off of accuracy assessment results, are primarily due to inaccuracies in the DWR-RTP technique.

While density is not directly measured with either FE or DWR-RTP techniques, results of this study indicate that calibrated FE data is similar to estimates made with DWR-RTP methods. Two potential solutions have been proposed for calibrating FE estimates (Eq. 1 or Eq. 2). Estimates derived from Eq. 1 have shown the highest correlation to the DWR-RTP data, with a near 1:1 relationship, therefore we would suggest the use of Eq. 2 in calibrating FE density data.

In general study sites used in this analysis were chosen by the DWR-RTP because of their forage potential for wildlife (Summers et al. 2007). Consequently, these sites still have an intact understory component and represent phase I and II woodlands (Miller et al. 2005), with several of the sites experiencing a high degree of P-J stand infilling and tree encroachment (Summers et al. 2007). We speculate that empirical calibration may be less important for phase III P-J woodlands, where mature trees are the dominant component. Because of this potential for the number of trees below the detection limit and undetectable trees to vary by site, some degree of in-situ calibration is necessary. Results indicate that the DWR-RTP density estimations were accurate and could be used to calibrate FE density. This could be useful for the DWR-RTP and other land management personnel by enabling them to incorporate FE techniques into their range trend evaluations. For instance, in-situ measurements performed by the DWR-RTP could be used in conjunction with FE techniques to estimate tree density on a much larger scale.

Where empirical calibrations are not possible or desirable, density data obtained through the proposed technique may still have application for land managers, depending on the use of the data. For instance, density extraction techniques proposed may still be suitable where management goals are to monitor rangeland trend, transitional phases, or assess wildlife habitat suitability.

Time Analysis

Time and resources required for estimating rangeland conditions is an important advantage of FE techniques (Seefeldt & Booth 2006). Time required for extracting tree cover and density for each site analyzed in this study ranged between 0.5-2.0 person-hours, depending on image quality and tree density. In a rough time analysis, the DWR-RTP estimates that it requires them approximately 18 person-hours to collect cover and density for a site (6-person crew x (average of 2.0 hours of travel time + 1.0 hour for transect set-up and tree cover/density parameter collection) = 18).

Conclusions

Feature extraction techniques used in this study provide a cost-effective procedure for assessing important rangeland indicators, including: density, cover, and extent of P-J tree encroachment. Additionally, correlations found between field plot data and remotely sensed imagery provides evidence to support extrapolation of cover data between the two approaches when assessing rangeland status.

We conclude that the proposed FE techniques used in this study are highly accurate in estimating tree canopy cover and are comparable to estimates derived by the DWR-RTP through the line intercept method. Tree density, estimated through FE techniques was also highly correlated to GR surveys, and estimates measured through the point-intercept method by the DWR-RTP. However, FE methods have the potential to underestimate tree density, primarily due to the techniques inability to detect seedling and sapling trees that are below the detection threshold.

We estimate that increased resolution could significantly increase the accuracy of our newly-developed FE density technique. From these results we postulate that an ideal resolution for tree density extraction would be around 0.0347m if the extraction of all but seedlings and unextractable trees is desired. Future work should be conducted at different resolutions to help land managers and research personal understand the appropriate resolutions needed to answer their specific objectives.

Calibration of FE data with GR measurements can also overcome detection limitations and produce a near 1:1 relationship to DWR-RTP estimates. Because of the high accuracy of the DWR-RTP to GR, range trend plots throughout the state could also be used for calibration of FE density data. Such approaches are desirable because the number of undetectable trees may vary with site. While increased resolution could improve accuracy of extracting tree density through FE techniques, it is important to note that a small percentage of trees growing in a conglomerate with other trees or seedlings underneath larger trees may never be detected regardless of resolution. Coupling field-based measurements with FE techniques magnifies both measurement types, allowing FE data to be calibrated with actual tree counts, and allowing for monitoring to take place at the landscape rather than the plot level.

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TABLES

Table 1. Error matrix showing number of sample points stratified between feature- extracted tree and non-tree locations, and the classification accuracy and Kappa statistic, tested on-screen and in-situ.

On-screen

Classified data	Tree	Non-tree	Total	User's Accuracy
Tree	[illegible]	79	[illegible]	[illegible]
Non-tree	[illegible]	[illegible]	[illegible]	[illegible]
Total	[illegible]	[illegible]		
Producer's Accuracy	[illegible]	[illegible]		
Overall Accuracy		[illegible]		
Kappa Statistic		[illegible]		

In-situ

Classified data	Tree	Non-tree	Total	User's Accuracy
Tree	194	16	210	[illegible]
Non-tree	[illegible]	[illegible]	210	[illegible]
Total	[illegible]	[illegible]		
Producer's Accuracy	[illegible]	[illegible]		
Overall Accuracy		[illegible]		
Kappa Statistic		[illegible]		

Table 2. Summary statistics and the percent difference between: ground reference (GR), feature extracted (FE), and Division of Wildlife Resources Range Trend Project (DWR-RTP) measurements approaches for plots selected for accuracy assessment.

Accuracy Assessment									
Summary Statistics					Relative Percent Difference				
Method	N	Mean	SE	Range	Comparison	N	Mean	SE	Range
Cover		------------- % -------------			Cover		------------- % -------------		
GR	7	15.0[illegible]	3.4	6.8-28.8	GR vs FE	7	11.0^{a}	[illegible]	0.3-26.3
FE	7	14.1^{a}	3.3	5.0-27.9	GR vs DWR-RTP	7	29.9[illegible]	[illegible]	1[illegible]-61.5
DWR-RTP	7	1[illegible]	2.2	4.8-[illegible]9.1	FE vs DWR-RTP	7	27.[illegible]	7.5	6.6-58.4
Density		---------- trees ha^{-1} ----------			Density		------------- % -------------		
GR	7	214.8[illegible]	42.5	28.8-339.6	GR vs FE	7	38.[illegible]	[illegible]	16.5-62.7
FE	7	[illegible]7.0^{b}	23.5	25.5-220.6	GR vs DWR-RTP	7	21.6[illegible]	10.0	3.4-73.0
DWR-RTP	7	203.2[illegible]	42.4	41.0-3[illegible]	FE vs DWR-RTP	7	48.0^{a}	8.6	18.3-81.9

N = plots sampled; SE = standard error.
Means with[illegible] a common letter [illegible] differ at P [illegible] .05

Table 3. Tree cover and density data not extracted from 7 DWR-RTP sites, through feature extraction techniques, as compared to ground reference. Total tree cover estimated through ground reference techniques was found to be 4,617.3 m^2; total number of trees counted equaled 684.

Types of trees not extracted from imagery	Cover		Density	
	Area (m^2)	Percent of total	Count	Percent of total
Underneath larger trees	[illegible]	0.0%	62	[illegible]
Conglomerate with larger trees	[illegible]	0.0%	9	1.3%
Proximity to larger trees	[illegible]	0.0%	31	4.5%
Below detection limit	47.13	1.0%	163	23.8%
Total	47.13	1.0%	265	38.7%

Table 4. Summary statistics and the percent difference between: ground reference (GR), feature extracted (FE), and Division of Wildlife Resources Range Trend Project (DWR-RTP) measurements approaches for all plots tested (global data set).

Global Data Set									
Summary Statistics					Relative Percent Difference				
Method	N	Mean	SE	Range	Comparison	N	Mean	SE	Range
Cover	%				Cover	%			
FE	32	14.3[a]	2.1	0.9-47.8	FE vs DWR-RTP	31	41.3	8.9	1.7-197.6
DWR-RTP	32	14.1[a]	2.2	0.0-44.8					
Density	trees ha^{-1}				Density	%			
FE	34	149.3[a]	18.6	5.6-544.[illegible]	FE vs DWR-RTP	31	53.9[a]	7.6	2.8-182.4
FE (cal. Eq.1)	34	243.8[b]	30.3	9.0-857.6	FE (cal. Eq.1) vs DWR-RTP	31	44.5[a]	8.4	0.6-245.0
FE (cal. Eq.2)	33	236.4	32.8	[illegible]	FE (cal. Eq.2) vs DWR-RTP	31	40.6[a]	5.9	6.8-172.0
DWR-RTP	34	254.9[b]	34.9	0.0-773.4					

N = plots sampled, SE = standard error.
Means without a common letter differ at P < 0.05.

FIGURES

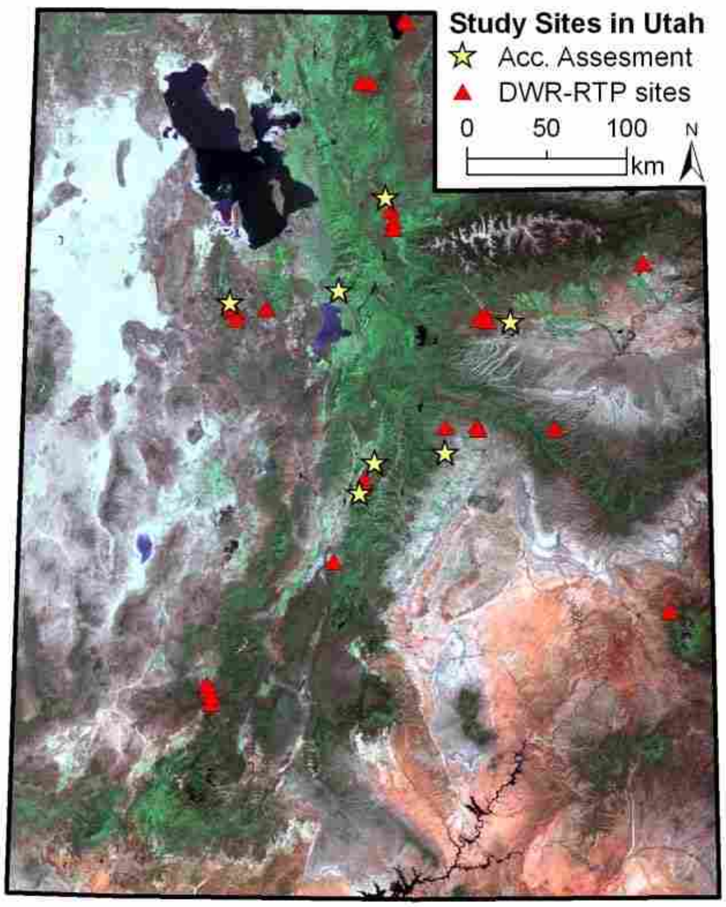

Fig. 1. Landsat TM imagery (Utah State University, 2001) of the state of Utah, overlaid by Utah Division of Wildlife Resources Range Trend Project (DWR-RTP) locations analyzed through feature extraction techniques, and those DWR-RTP sites for which ground reference measurements were also performed for in-situ accuracy assessments. Imagery obtained from Intermountain Region Digital Image Archive Center, Utah State University.

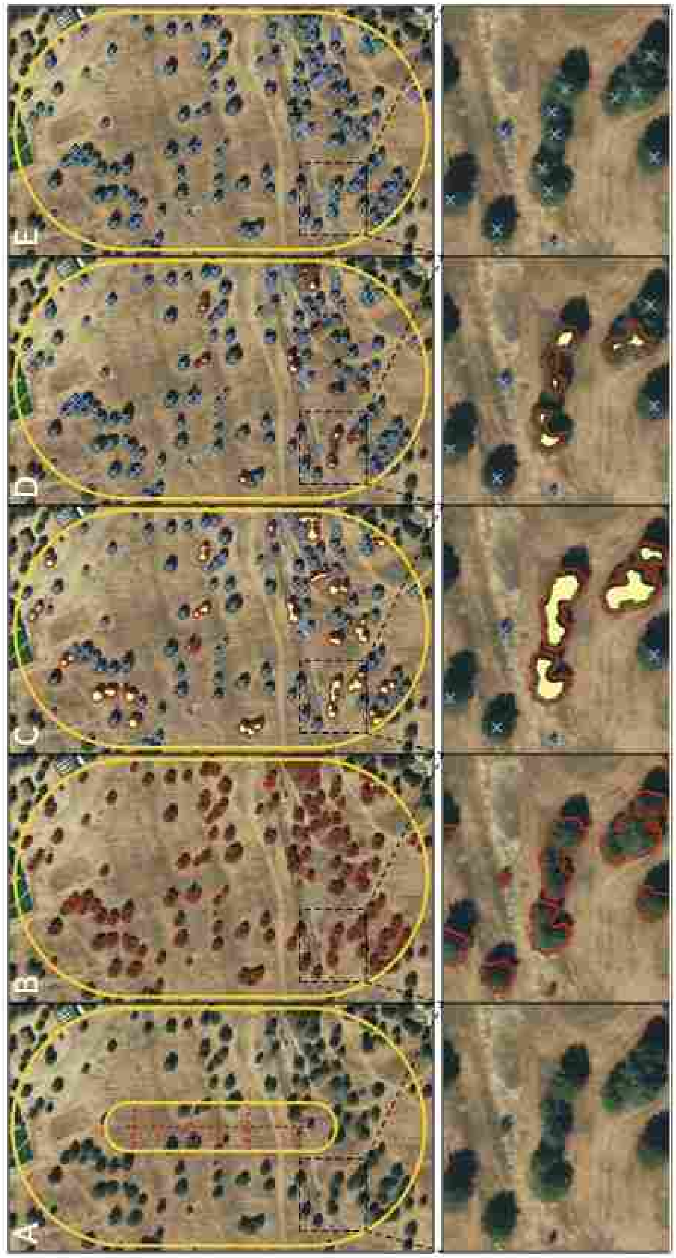

Fig. 2. (A) Utah Division of Wildlife Resources Range Trend Project (UDWR RTP) 121.9 m baseline transect and associated 30.5 m transects displayed as dashed red lines; 15.3 m and 75 m plot buffers shown in gold. (B) Final feature extraction results of tree cover shown in red. (C) Feature extracted polygons representing individual trees were converted to points, shown as blue X's; polygons representing multiple individuals had a negative buffer technique applied, results shown in light yellow. (D) Results from the negative buffer technique were then sorted by area and smaller polygons representing individuals were converted to points (blue X's); larger polygons (outlined in red) had a second negative buffer applied (light yellow). (E) Final density extraction results from polygons representing individual trees which were then converted to points (blue X's).

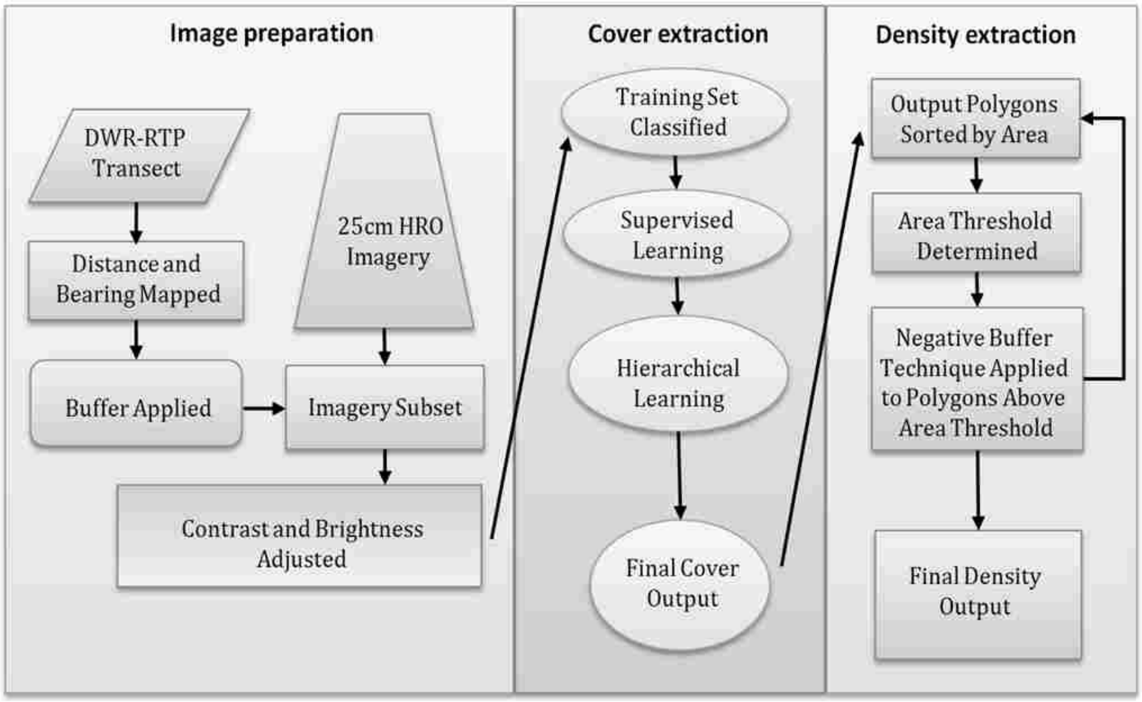

Fig. 3. Flow diagram of the feature extraction process to derive tree cover and density.

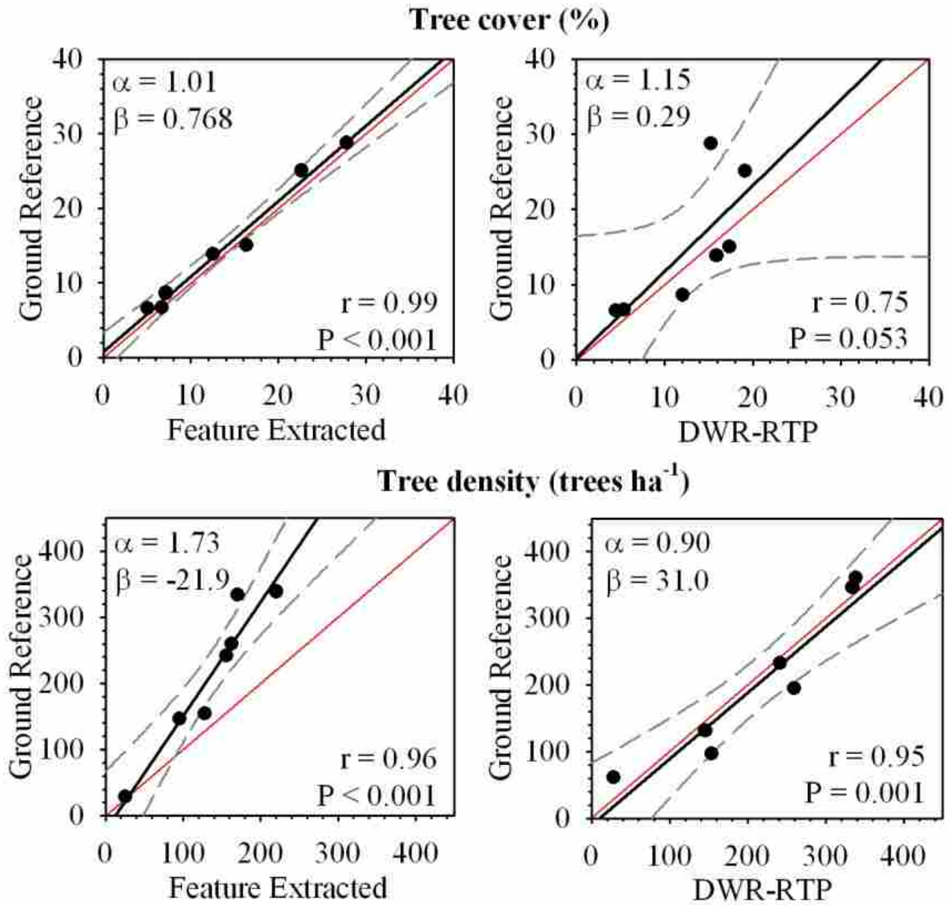

Fig. 4. Linear regression analysis for tree canopy cover and density accuracy assessment results; comparing ground reference, Utah Division of Wildlife Resources Range Trend (DWR-RTP), and feature extracted data. Correlation line and confidence intervals at 95 % is show in relationship to the data. A 1:1 line is draw in red for reference of a perfect correlation (i.e. y = x). Correlation coefficient, *r*, and p value are shown, with $P < 0.05$ indicating a significant relationship.

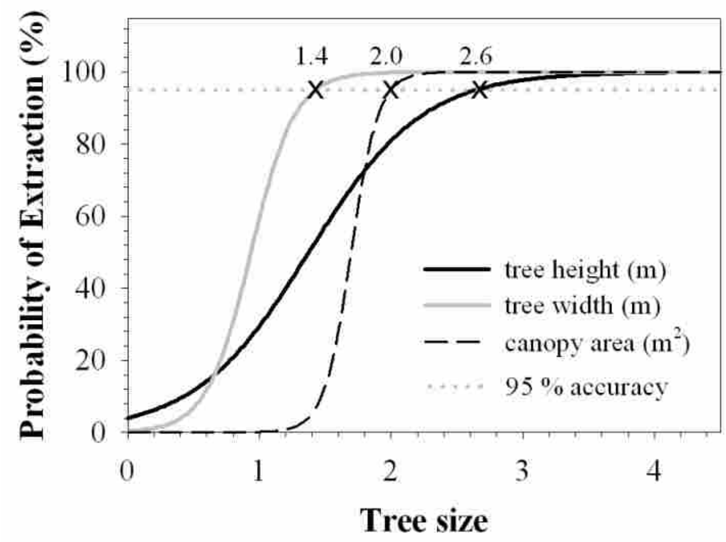

Fig. 5. Logistic regression models predicting the probability of tree extraction based on tree height, mean canopy width, or canopy area. Detection limit at 95 % accuracy is shown by a dashed horizontal line.

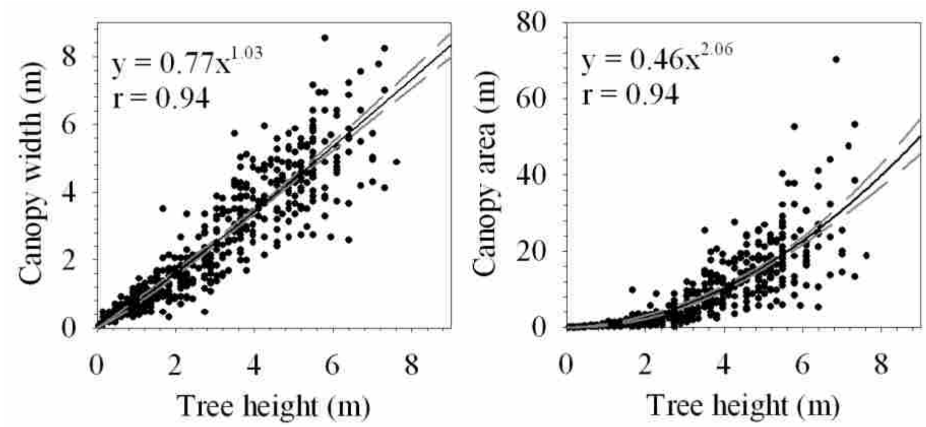

Fig. 6. Scatter plot for tree height and mean canopy width estimated from 684 trees sampled within 7 DWR-RTP sites. The data was best-fit by a power regression line. This line and confidence intervals at 95 % is show in relationship to the data. Correlation coefficient, *r*, and p value is shown, with $P < 0.05$ indicating a significant relationship.

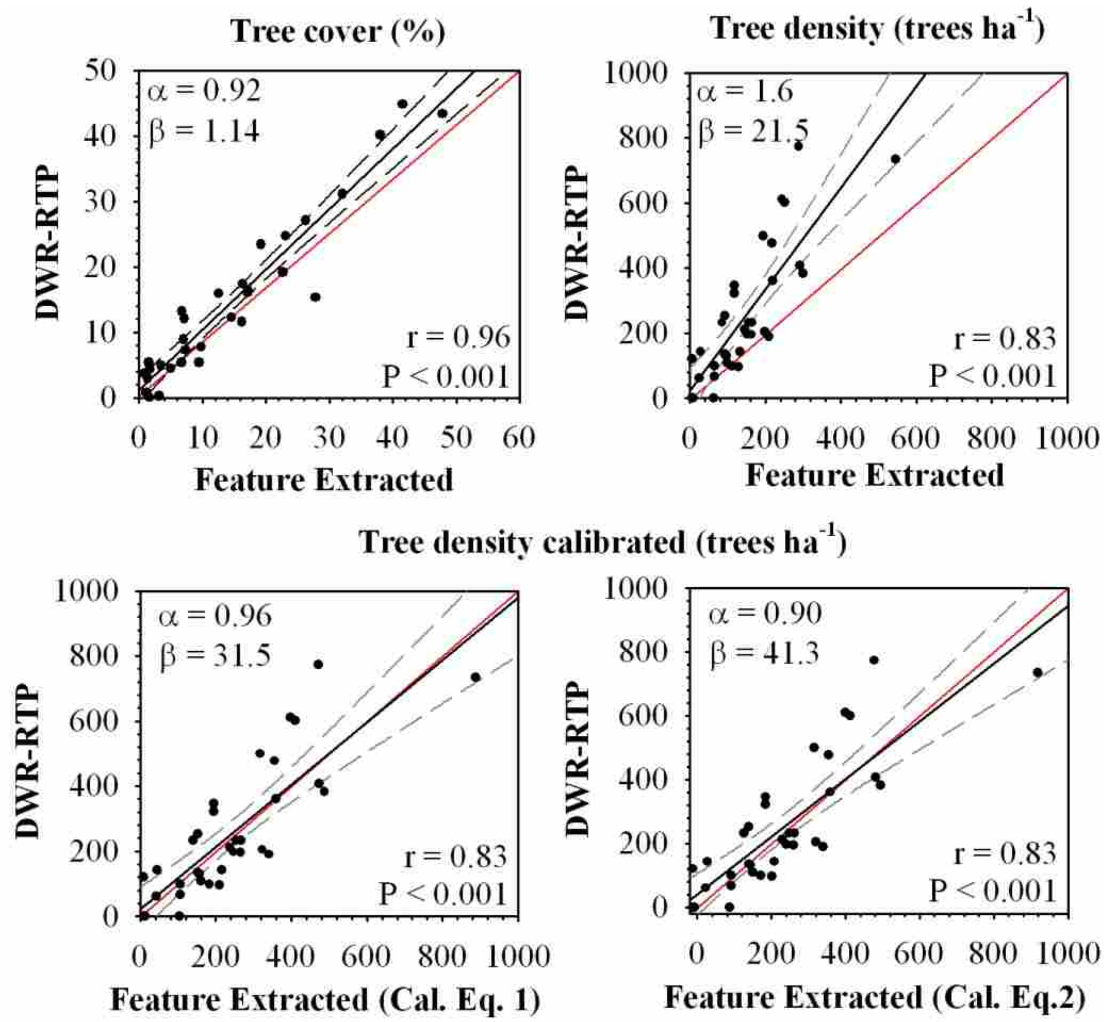

Fig. 7. Linear regression analysis for tree canopy cover and density global data sets; comparing Utah Division of Wildlife Resources Range Trend (DWR-RTP), and feature extracted data. For density correlation is also shown between DWR-RTP and Feature Extracted data calibrated by increasing each measurement point according to Eq. 1, and Eq. 2. Correlation line and confidence intervals at 95 % is show in relationship to the data. A 1:1 line is draw in red for reference of a perfect correlation (i.e. y = x). Correlation coefficient, *r*, and *P* value is shown, with $P < 0.05$ indicating a significant relationship.

Chapter 3: Post-fire Soil Water Repellency within a Piñon-Juniper Ecosystem: Assessment of the Milford Flat Wildfire

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ABSTRACT

Post-fire recovery of juniper dominated ecosystems is dependent on the extent that ecological processes have been altered. Soil water repellency is a common condition in these ecosystems that can limit site recovery by decreasing plant soil water availability and increasing runoff and soil erosion. In this study we examined the influence of post-fire soil water repellency on ecohydrologic properties in a burned piñon-juniper (*Pinus-Juniperus*) (P-J) woodland, and the spatial distribution and intensity of soil water repellency relative to pre-burn juniper canopy cover. Several fine scale infiltration measurements were performed along radial line transects from the bolus of burned juniper trees to twice the canopy radius, under wet and dry soil conditions. Measurements included: soil water repellency depth and severity, soil water content, and unsaturated hydraulic conductivity measured using water and a surfactant solution. Results were exported into a GIS based model and used in conjunction with remotely sensed imagery to estimate the spatial distribution of soil water repellency at the landscape scale. Results indicate that post-fire patterns of soil water repellency are highly correlated with pre-fire P-J woodland canopy cover; critical water repellency extended from the base of the tree to just beyond the canopy edge, while sub-critical water repellency extended from the edge of the critical water repellency zone to two times the canopy radius. At sites where critical soil water repellency was present, infiltration rate, soil moisture, and vegetation cover and density were significantly reduced, relative to non-water repellent sites. These variables were also reduced in soils with sub-critical water repellency (albeit to a lesser extent). GIS and remotely sensed imagery, combined with field-based spatial measurements, provide an effective method for assessing post-fire impacts at the landscape scale.

Abbreviations: WDPT, water drop penetration time; SWC, soil water content; $K(h^w)$, unsaturated hydraulic conductivity measured with water; $K(h^s)$, unsaturated hydraulic conductivity measured with a surfactant solution; P-J, piñon (*Pinus*) and juniper (*Juniperus*) vegetation; GIS, geographic information systems; CR, canopy radius

1. Introduction

The pronounced expansion of woody vegetation in semi-arid ecosystems has been observed globally (Van Auken, 2000; Briggs et al., 2002; Huxman et al., 2005; Breshears, 2006). Proposed primary causal factors include high intensity grazing, fire suppression (Bragg and Hulbert, 1976; Heisler et al., 2003), increased atmospheric CO_2 concentrations (Mayeux et al. 1991; Johnson et al. 1993), and climate change (West, 1999; Miller and Tausch, 2001; Romme et al., 2009). In the Western United States, the range of expansion and stand infilling by piñon (*Pinus*) and juniper (*Juniperus*) (P-J) species into grassland and sagebrush communities constitutes one of the greatest afforestations of our time (Miller et al., 2008). Since European settlement of the Western US, these species have expanded their range to more than 40 million hectares (Romme et al., 2009). This ecosystem shift has impacted soil resources, plant community structure and composition, forage quality and quantity, water and nutrient cycles, wildlife habitat, and biodiversity (Miller et al., 2008). As P-J woodlands mature, increased fuel loads and canopy cover can lead to large scale, high intensity crown-fires (Miller and Tausch, 2001; Miller et al., 2008). After a fire, the ability of a P-J dominated ecosystem to recover depends on the extent that physical and biological processes controlling ecosystem function have been altered, both prior to and as a result of the fire (Briske et al., 2005, Miller and Tausch, 2001; Petersen and Stringham, 2008).

Prior studies suggest that water repellency acts as a temporary ecological threshold impairing site recovery by increasing soil erosion, and impairing the establishment of desired species within the first few years after a fire (Krammes and DeBano, 1965; Krammes and Osborn, 1969; DeBano, 1981; Letey, 2001; Chapter 3 herein), which may leave resources available for weed invasion after soil water repellency has diminished. In light of these ecological concerns, understanding the extent, severity and spatial patterns of soil water repellency may help guide land managers in conducting restoration efforts after a fire. Madsen et al. (2008) found that in unburned conditions, soil water repellency was confined to the soil directly below tree canopies. However, their water repellency assessments were performed with the water drop penetration time (WDPT) test, which is only sensitive to contact angles greater than 90 degrees. In the same study the authors found that unsaturated hydraulic conductivity (K(h)) at -2 cm continued to increase along a gradient past the canopy edge, out to two times the canopy radii. These measurements may indicate that beyond the detected water repellence zone, subcritical water repellency (Wallis et al., 1991; Tillman et al., 1989; Hallett et al., 2001; Hallett et al., 2004) was suppressing infiltration.

Assuming that there is a similarity between pre-canopy cover and post-fire soil water repellency patterns, we hypothesize that the relationship between pre-burn canopy cover and soil water repellency can be used to estimate the extent of soil water repellency at the fire boundary scale, using GIS and pre-burn remotely sensed imagery. For example, the integration of field based measurements with feature extracted data acquired from remotely sensed imagery can enable assessment of rangeland conditions over large land areas (Hunt et al., 2003). Feature extraction techniques for classifying tree cover using high resolution panchromatic and multispectral data have been implemented by several authors (i.e. Weisberg et al., 2007; Everitt et al., 2007; Afinowicz et al., 2005; Petersen et al., 2005; Harris et al., 2003; and Hunt et al., 2003). These authors used feature extraction software to segment tree cover from the surrounding landscape on the basis of spatial, textural, and spectral data. We propose that the spatial distribution of soil water repellency can be extrapolated to the fire boundary scale by applying plot scale spatial rules to patterns of pre-burn canopy cover obtained from remotely sensed imagery.

The experimental goals of this study were: first, determine the spatial distribution and severity of post-fire soil water repellency, and its correlation to soil moisture, infiltration capacity, and revegetation recovery. Second, relate these patterns in ecohydrologic properties to pre-fire juniper canopy cover and post-fire vegetation establishment. Third, demonstrate a GIS based approach to scale-up observed patterns in soil water repellency to the fire boundary scale, using pre-burn remotely sensed imagery.

2. Materials and Methods

Two field studies were conducted within the boundary of the Milford Flat fire. On 6 July 2007 the Milford Flat fire was ignited by lightning. Upon its containment on 10 July 2007, the fire had burned 145,000 ha, becoming Utah's largest wildfire on record. Prior to the fire, singleleaf piñon (*Pinus monophylla* Torr. & Frém.) and Utah juniper (*Juniperus osteosperma* (Torr.) Little) occurred in 23 % of the burned area in a wide range of stand densities and ecological site types. The soils within the fire boundary are predominantly alluvium derived from igneous and sedimentary rock from the Mineral Mountain range with texture primarily ranging from loam to sandy loam (Soil survey staff, 2009).

2.1 Study 1: Winter sampling

The first study was performed to quantify the spatial distribution and severity of water repellency, and its effect on soil water content, throughout the fire boundaries. Fieldwork was conducted 4-9 January 2008. This study was timed to immediately follow a period of above average air temperature and light rain that melted most of the surface snow, thawed the soil profile and wet the upper hydrophilic soil layer, thereby providing the conditions necessary for optimal field sampling. Sampling was performed on 47 reference sites randomly selected within moderate to high intensity burned P-J woodlands. Spatial burn intensity data were acquired from Burned Area Reflectance Classification (BARC) maps developed by the Remote Sensing Applications Center (Salt Lake City, UT). Boundaries of P-J woodlands were determined from the land cover mapping portion of the 2004 Southwest Regional Gap Analysis Project (SWReGAP). (http://earth.gis.usu.edu/swgap/). Reference points were randomly generated in Hawths Tools 3.2 extension (Beyer, 2004) for ArcGIS® 9.3 (ESRI, Redlands, CA).

In the field, a GPS 60 navigator (Garmin Ltd., Olathe, KS) was used to locate the preselected reference points, and the nearest tree was identified as a datum for the survey of soil properties. Soil water content (SWC) and soil water repellency were measured *in situ* at 20 cm intervals along radial line transects that extended outward from each tree trunk to one canopy radius past the canopy edge. Soil water content was measured between 2.0-5.5 cm below the soil surface, with an ML2x Theta Probe (Delta-T Devices, Cambridge, England). Water repellency was measured with the WDPT test (Krammes and DeBano, 1965). Soils were considered water repellent if WDPT exceeded 5 seconds. To determine the depth to the water repellent layer from the soil surface, WDPT tests were performed at 0.5 cm depth increments, from the soil surface, in a pit excavated midway between the tree trunk and the burned canopy edge. In the same pit, a soil sample was collected from the water repellent layer. In the laboratory these samples were used to assess the severity of the water repellent layer by placing 2 separate drops of water (0.17 ml per drop) on the soil surface, and recording the time to enter the soil.

2.2 Study 2: Summer sampling

The second study was designed to quantify, under low soil moisture conditions, similar parameters as measured during the winter campaign, and to test the persistence of water repellency, its influence on soil infiltration, and impact on revegetation establishment one and two years following fire. This study was conducted, on 3 June 2008 and 13 July 2009. To limit the effects of landscape scale heterogeneity in soil moisture and texture, and minimize the time costs associated with conducting a fine spatial scale survey, this study was confined to five juniper trees within a 0.5 ha area.

Soil within the 0.5 ha study area was a coarse sandy loam, mixed, mesic Aridic Haploxerolls (Soil Survey Staff, 2009). The site was modestly sloping (3-10 %), and predominantly west facing. Mean annual precipitation at the site was 370 mm (PRISM Climate Group, 2009). Prior to the fire, the vegetation community was a Phase III P-J woodland (i.e. “trees are the dominate vegetation and primary plant layer influencing ecological processes on the site”) (Miller et al., 2005). The site was aerially reseeded at 8-12 lbs pure live seed ha^{-1}, with a mix of desired non-native species provided by the Bureau of Land Management and Division of Wildlife Resources.

To assess the influence of water repellency, we measured 7 ecohydrologic parameters every 30 cm along a randomly oriented transect extending 5 m from the base of each tree, for a total of 85 sampling points per year. Measurements included: extent, depth and severity of soil water repellency, SWC, unsaturated hydraulic conductivity (K(h)), and understory vegetation cover and density (2009 only). The extent, depth, and severity of soil water repellency, and SWC were measured as previously described. Two infiltration measurements were taken at each sampling interval, one using water ($K(h^w)$), and the second using a surfactant solution designed to overcome water repellency (2.04 % v/v solution of IrrigAid Gold, Aquatrols, Paulsboro, NJ) ($K(h^s)$). This approach allowed us to estimate the influence of soil water repellency on unsaturated infiltration, even where water repellency was not detectable through the WDPT test (i.e. subcritical water repellency). Automation methods, measurement procedures, and calculations were performed according to Madsen and Chandler (2007). We chose to make measurements at -2.0 cm head to maximize spatial replication, at the expense of characterizing K(h) at several head values. All K(h) measurements were corrected to standard temperature (20 °C) by the viscosity ratio approach of Constantz (1982). Unsaturated hydraulic conductivity was calculated from infiltration at an approximately steady state. Ocular estimates of vegetation cover were estimated by species, within 25 × 25 cm quadrats (0.0625 m^2); plant density was directly measured within the same quadrats.

2.3 Data analysis

In order to provide consistency among trees with variable pre-burn canopy widths, sampling locations were normalized spatially by dividing the distance of the measurement location from the center of the tree by the canopy radius of the tree it was measured at. Following normalization, data were grouped into 0.25 canopy radii (CR) intervals for statistical analyses. For example, 0.50 CR is the point midway between a tree's trunk and the canopy edge and would include all normalized measurement intervals between 0.25 and 0.50 CR. Statistical analyses were performed with Sigma Stat 3.1 (Systat Software, Inc. Richmond, CA). For all comparisons, a significance level of $P < 0.05$ was used. Because the data did not meet assumptions of normality (tested using the Kolmogorov-Smirnov test), Mann-Whitney rank sum tests were used for all pairwise comparisons between quartiles. Correlations among the ecohydrologic parameters measured in this study were analyzed separately within each field campaign using a Spearman Rank correlation test, with results presented as correlation coefficients *r* and significant *P* values.

To determine if the amount of pre-burn P-J cover across the landscape influenced the presence and severity of soil water repellency under individual trees, we estimated pre-burn P-J tree canopy cover within the fire boundaries. Pre-burn P-J cover data were extracted from near-infrared, 1 m^2 aerial photography, obtained from the NAIP database. In ERDAS Imagine® (ERDAS Inc. 2006) a 3 × 3 low pass convolution filter was applied to reduce image variability. A supervised classification procedure was performed using a maximum likelihood parametric rule to produce a Boolean image of P-J tree areas and non-tree areas. From the resultant dataset we calculated juniper canopy cover as the percentage of pixels classified as tree cover within a 30 m diameter moving window, similar to the approach of Afinowicz et al. (2005). A Spearman Rank correlation test was used to determine if tree canopy cover and the measured ecohydrologic properties were correlated.

Field results of soil water repellency measured along radial line transects which extended out from individual trees, were up-scaled using pre-burn color inferred (CLR) imagery and GIS technology through a technique we have designated as the “radial feature extraction technique” (RFET). Imagery used in this study was flow in the summer of 2006, and obtained from the Utah Automated Geographic Reference Center (AGRC, 2008). Methods used for the RFET comprised converting the Boolean output file showing tree cover created previously into a vector file in which individual trees were represented by polygons. The area of each polygon, A_p, was calculated within the attribute table. With the assumption that each polygon represented an individual tree and was circular in shape, the radius of each polygon (tree) in the image was calculated and then multiplied by the normalized canopy radii distance of the water repellency parameter of interest, z, to obtain the buffer distance, B, for each polygon in the landscape:

$$B = z\sqrt{\frac{A_p}{\pi}}$$

This buffer distance was then applied to the original polygon/tree shapefile in ArcGIS to determine the area of effect for the various water repellency parameters of interest. The RFET was demonstrated using the 2008 summer field sampling data, with results extrapolated to a 50 ha area that contained similar soil and tree cover properties as observed at the locations of our field measurements.

3. Results

3.1 Winter sampling

In the winter campaign, soils were found to be water repellent on 87.5 % of the trees sampled. For trees with hydrophobic soils, the average WDPT was 84 minutes. On average 51.9 ± 4.9 % of each burned canopy area was found to be water repellent. Soil water repellency occurred as a layer that extended from near the tree trunk (0.08 ± 0.01 CR) to 0.74 ± 0.04 CR (Fig. 1). In the center of this zone, soil water repellency averaged 4.8 ± 0.51 cm thick, with an average minimum depth of 1.4 ± 0.12 cm (Fig. 1). Results from the winter campaign did not show any significant correlations among the ecohydrologic parameters measured.

Significant differences in SWC were found among CR intervals under trees where soil water repellency was found, with SWC ranging from 11.44 ± 0.73 % at 0.50 CR to 25.20 ± 0.78 % at CR 2.00 (Fig. 1). The 0.25 and 0.50 CR intervals evidenced similar SWC. Beyond 0.50 CR, SWC increased out to 1.25 CR. From 1.25 to 2.00 CR there were only slight increases in SWC values; SWC values between 1.00 and 1.25 CR were significantly less than those between 1.5 and 2.00 CR, but no differences were observed between 1.25 and 2.00 CR. Conversely, on trees that did not exhibit soil water repellency, SWC was similar regardless of distance from the tree ($P = 0.142$), with an average SWC of 26.54 ± 0.72%.

3.2 Summer sampling

Results of soil water repellency tests and infiltration measurements are shown in Fig. 2. All trees measured in the summer campaign were water repellent in 2008 and 2009. In 2008, water repellency extended from the tree trunk to 1.25 CR, with an average WDPT of 87.6 ± 4.28 minutes. In 2009, water repellency depth, extent and severity were similar to 2008 with the exception that WDPT increased slightly ($P = 0.006$) at 1.50 CR, and thin (less than 1.0 cm) variable, water repellent layer was detected from 1.25-2.00 CR.

In 2008, the depth to the water repellent layer was similar between 0.25-0.75 CR, with an average depth of 1.71 ± 0.16 cm. At 1.00 CR the minimum depth to the water repellent layer decreased to 0.92 ± 0.22 cm, which was significantly shallower than observed at all locations closer to the center of the canopy except at 0.25 CR. This trend continued at 1.25 CR, where water repellency depth decreased to 0.37 ± 0.14 cm. Water repellency thickness and maximum depth of the water repellent layer declined as distance from the tree increased. The thickness of the water repellent layer averaged 4.54 ± 0.24 cm, under the burned canopy region. This value was similar to the water repellency thickness obtained in the 2008 winter measurement campaign under “wet” conditions. Beyond the canopy edge, thickness of the water repellent layer decreased significantly. At 1.25 CR, average water repellent layer thickness was 1.66 ± 0.61 cm, and water repellency was seldom detected beyond this distance. The only decrease in water repellency thickness from 2008 to 2009 occurred near the canopy edge at 1.00 CR, where the thickness of the water repellent layer decreased by 1.96 ± 0.62 cm.

Infiltration of water was complimentary to WDPT, whereas infiltration of the solution with surfactant was apparently accentuated by water repellent soil (Fig. 2; Table 1). As expected, $K(h^w)$ was lowest where water repellency was most pronounced. In 2008, $K(h^w)$ was near zero from 0 to 0.75 CR; beyond this point, $K(h^w)$ steadily increased out to 1.50 CR, with $K(h^w)$ equal to 10.1 ± 1.9 cm hr^{-1}. No differences in $K(h^w)$ were observed beyond 1.50 CR. In 2009, $K(h^w)$ values were similar to the values observed in 2008. Infiltration using a surfactant solution showed the highest values in areas with severe water repellency. Under the canopy, $K(h^s)$ averaged 33.1 ± 1.0 cm hr^{-1} in 2008. Beyond the pre-burn canopy edge $K(h^s)$ dropped significantly, reaching a minimum of 9.8 ± 2.1 cm hr^{-1} at 2.00 CR, which value did not differ from $K(h^w)$. Because water repellency was only detected out to 1.25 CR with water drop tests, these results most likely indicate that there is a zone of subcritical water repellency that extends beyond 1.25 CR out to 2.00 CR. In 2009 $K(h^s)$ values were found to be significantly lower than 2008 values in the burned canopy soil, but not significantly different in intercanopy soil. On average $K(h^s)$ for all canopy quartiles dropped to 20.6 ± 1.1 cm hr^{-1}, and were not significantly different from intercanopy measurements at 1.25 CR or 1.50 CR. Beyond 1.50 CR, $K(h^s)$ dropped to 10.7 ± 1.5 cm hr^{-1} at 1.75 CR, where $K(h^w)$ and $K(h^s)$ were similar. These results indicate that the extent of subcritical water repellency shifted from 2.00 CR in 2008 to 1.75 CR in 2009.

For both summer campaigns SWC increased with distance from the tree trunk, similar to the pattern observed in the winter campaign (Fig. 3). In 2008, SWC ranged from 0.013 ± 0.002 % at 0.25 CR to 0.027 ± 0.001 % at 2.00 CR. Within the 2008 dataset, SWC was near zero from 0.25 to 0.75 CR. A clear gradient in SWC emerged between 0.75 CR and 1.75 CR, but beyond that point SWC remained similar among canopy radii. Within the 2009 dataset a similar relationship was found.

Overall plant density was 31.6 plants m^{-2}. Establishment of seeded species was a near zero, composing only 1.52 % of the total density (0.48 plants m^{-2} seeded species and 31.12 plants m^{-2} of non-seeded species). Total plant density in the canopy area was similar among quartiles with an average of 3.05 ± 1.12 plants m^{-2} and significantly less than in the intercanopy where density averaged 60.88 ± 6.33 plants m^{-2} (Fig. 4). Within the intercanopy, plant density also appeared to increase with distance from the bolus (Fig. 4).

The relationship of seedling density and distance was not consistent between species. The three most dominant plant species at the site were *Gilia inconspicua* (Sm.) Sweet (shy gilia), *Bromus tectorum* L. (cheatgrass), and *Nicotiana attenuata* Torr. ex S. Watson (coyote tobacco). Within the burned canopy, density of *G. inconspicua* and *B. tectorum* was near zero (0.13 ± 0.07 plants m^{-2}, and 0 ± 0 plants m^{-2} respectively), but increased in the intercanopy (3.45 ± 0.38 plants m^{-2}, and 0.09 ± 0.03 plants m^{-2} respectively). No difference was observed for *N. attenuata* between canopy (0.02 ± 0.02 plants m^{-2}) and intercanopy (0.02 ± 0.02 plants m^{-2}) density values (Fig. 5).

The relationship between cover and distance from the tree trunk is displayed in Fig. 6. Compared with the pattern exhibited by plant density, increases in cover with distance from tree trunk were less abrupt and more variable. Much of the variability in plant cover was attributable to *N. attenuata*. Analyzing cover data without *N. attenuata* reduced variability among the quartiles. Without *N. attenuata*, no significant differences were observed between cover values from 0.25-1.25 CR (average 0.32 ± 0.95 %); beyond 1.25 CR, cover values increased significantly, but were similar among quartiles, averaging 2.27±0.315 %.

3.3 Remote sensing and GIS analysis

Fig. 7 shows the results of our proposed RFET method which upscale field measurements from individual trees to the landscape scale, using GIS and aerial photography. With 23 % juniper canopy cover on the site, we calculated that 81 % of the area was influenced by water repellency, with 33 % exhibiting critical water repellency and 48 % influenced by subcritical water repellency. Visual assessment of the produced map shows that the modeling technique for estimating critical and subcritical water repellency is accurate where individual trees are found. In situations where multiple trees are represented by one polygon, the model may overestimate or underestimate the actual extent of water repellency. Additional research and likely higher resolution imagery will be needed to overcome this limitation.

4. Discussion

To the best of our knowledge this study is unique in that it is the first to quantify the spatial distribution of soil water repellency and associated ecohydrologic attributes important for post-fire revegetation success, within a P-J woodland. Other P-J woodland studies have noted the presence of water repellency and impacts to infiltration (Roundy et al. 1978; Rau et al., 2005), but none have looked at the spatial distribution of water repellency in the detail that we have and quantified its correlation to SWC, infiltration, and vegetation recovery. Results of this study are consistent with previous studies conducted in unburned P-J woodlands with similar sampling designs (Lebron et al., 2007; Madsen et al., 2008), where the total area influenced by soil water repellency was directly related to the extent of pre-burn tree canopy cover (Table 1, Fig. 8).

In this study the severity of water repellency was highly correlated with reductions in SWC, infiltration, and understory seedling density and cover (with the exception of *N. attenuata*). Even during the winter campaign when precipitation inputs were high, SWC was significantly lower where water repellency was present.

The extent to which subcritical water repellent soil was correlated with SWC, infiltration, and vegetation recovery was also clarified. Data from the winter sampling period showed that SWC did not increase abruptly immediately beyond the water repellent zone detected with the WDPT tests. Results from the summer sampling periods indicate that this result may be due to the presence of subcritical water repellency (Fig. 2). In the summer campaigns, infiltration analysis through $K(h^w)$ and $K(h^s)$ measurements showed that while critical water repellency was found to extend just beyond the pre-burn canopy edge (1.25 CR), subcritical water repellency extended to two times the canopy radius (2.00 CR) (Fig. 8). If we assume that the P-J trees are roughly circular in shape, an increase in water repellency extent from 1.25 CR to 2.00 CR translates into a 156 % increase in the extent of the water repellent area over that detected through WDPT tests. Because subcritical water repellency is also correlated with low SWC, infiltration, and understory seedling density and cover (albeit to a lesser extent than critical water repellency levels), these results provide justification for measuring both water repellency and subcritical water repellency when assessing post-fire soil hydrologic conditions.

The effect of soil water repellency is rarely considered in post-fire rangeland restoration efforts. To our knowledge this is the first wildfire research paper that has discussed the correlation and potential impact of subcritical water repellency on post-fire hydrologic and vegetative responses. Particularly within forested and chaparral conditions on Forest Service lands in the USA, the extent and severity of soil water repellency is generally quantified through WDPT tests; however, assessment of soil water repellency through standard WDPT's can be highly subjective, time consuming, and limited in both degree and scope (Hallett et al., 2001; Lewis et al., 2006). Recently Robichaud et al. (2008) has proposed that the mini-disk infiltrometer can be used to estimate the severity of soil water repellency. Results of this study also show that there is a significant correlation between WDPT tests and mini-disk infiltrometer measurements (r =-0.40 for 2008 sampling and r = -0.40 for 2009 sampling for correlation between $K(h^w)$ vs. WDPT) (Table 1). However, while a relationship maybe present, correlations are week in severely water repellent soils and there is no correlation for soils with subcritical water repellent levels. Methods used in this study were proven to be highly robust in detecting differences in the severity of soil water repellency even at subcritical levels. We propose that future research should be done in developing indices for this technique; potentially it could be adapted by land management agencies as a complementary procedure to methods already proposed by Robichaud et al. (2008).

Results of this study complement previous studies that have correlated observations of soil water repellency with areas of pre-burn canopy cover found to be devoid of vegetation for one or more years following a fire in P-J woodlands (Ott et al., 2001), desert scrub communities

(Adams et al., 1970), and sagebrush communities (Salih et al., 1973). In this study, though there was a slight decrease in subcritical water repellency, in general soil water repellency persisted for the length of the two year study, and its presence was mirrored by an impairment of vegetation recovery. Post-fire soil water repellency can limit revegetation success by decreasing soil moisture duration and availability to seeds and seedlings (Chapters 4 and 5 herein). As shown in Fig. 8 after a fire the soil consists of a shallow wettable layer overlying a water repellent layer which is several centimeters thick. Even if the wettable zone contains enough moisture for seed germination, due to the stratification from the underlying water repellent layer, there may not be adequate moisture for seedling survival. Moisture availability may also be decreased for seeds and seedlings as a result of the water repellency creating preferential flow channels, thereby lowering the total volume soil which is available for moisture retention in the upper centimeters of the soil profile (Blank et al., 1995).

For this study, establishment of seeded species was almost a total failure. Where water repellency was observed, seedling density (even of the small group of species that did grow) was near zero (Fig. 4). Beyond the zone of critical water repellency seedling densities significantly increased and were similar among species. However, a gradient was detected where seedling densities increased with distance from the tree (Fig. 4). Potentially this is the result of subcritical water repellency limiting seedling growth. Furthermore, the pre-burned tree composition of this woodland is such that the center of the intercanopy is generally located one canopy radius from the canopy edge (i.e. 2.00 CR). Consequently, the majority of the woodland was either dominated by water repellency or subcritical water repellency, which may be one reason why seedling establishment was poor overall at this site.

An exception to the patterns described above was observed in *N. attenuata* which grew well in the canopy and intercanopy region, with plant densities and cover for this species higher on average in the burned canopy region. This species is an early-successional, ephemeral species which occurs for 1 to 3 years after fire in sage-juniper habitats (Wells, 1959; Baldwin and Morse, 1994; Preston and Baldwin, 1999). Understanding the mechanisms which allow this species to establish within a severe water repellent soil could potentially help land managers and plant breeders select species with similar characteristics for post-fire reseeding projects.

Based on observations of post-fire recovery from previous fires near the study area, we would expect that within the next year or so *B. tectorum* will become the dominant species. Soil water repellency may negatively affect the germination and seedling establishment of seeded species and provide opportunities for invasion of annual weeds, such as *B. tectorum*, which can establish in the resource-rich canopy areas (Davis et al., 2000) after soil water repellency has diminished.

4.1 Application of GIS and remote sensing technology

Results of this study indicate that the REFT provides an effective method for assessing post-fire impacts at the landscape scale. Two of the primary benefits to the REFT approach are first, it allows fine-scale assessment of soil water repellency to be extrapolated at the landscape scale, and second, it allows for the predication of hydrologic responses beyond the canopy edge, such as subcritical water repellency and associated SWC and vegetative responses. Understanding the spatial contiguity of water repellency across the landscape has been suggested by Woods et al. (2007) as an important predictor of overland flow. Based off of the results of this study we would further suggest that soil water repellency is also an important indicator of vegetation recovery.

The REFT approach could be helpful for developing post-fire burn severity maps that could be used by land managers to detect the spatial contiguity of both water repellent and subcritical water repellent soil in order to better direct limited resources in applying water repellency-restoration strategies to enhance revegetation success, or mitigate landscapes that have a high potential for flooding and soil erosion.

In the United States, post-fire burn severity maps are typically produced primarily by the United States Forest Service Burned Area Emergency Rehabilitation (BAER) teams for identifying areas where fire-induced changes to soils have increased the potential for runoff and soil erosion (Parsons and Orlemann, 2002; Lewis et al., 2006). REFT methods proposed in this study are different from those used by the BAER team, primarily by producing finer scaled map of the water repellent layer and through its ability to predict soil water repellency impact with distance from the tree. As was used in this study we suggest BARC methods could first be used to determine fire boundaries, and then REFT methods could further refine the severity map.

The procedures in this study were limited by not including an accuracy assessment component. Future work should be performed to test the accuracy of this water repellency mapping technique. In addition, estimating the spatial distribution of soil water repellency using a combination of ground truth field measurements and remotely sensed data may be limited to within similar ecological sites within the fire boundaries. Prediction of post-fire water repellent soils could be improved by developing process-based models which predict the spatial distribution of soil water repellency from ecological site characteristics shown to have an influence on soil water repellency (i.e. soil texture, soil organic matter content and nature, pH, soil temperature, seasonal soil moisture, microbial activity, fungal hyphae, and topographic position (Debano, 1991; Crockford et al., 1991; Dekker and Ritsema, 2000; Doerr et al., 2000; Lewis et al., 2006).

5. Conclusions

Post-fire patterns of soil water repellency were highly correlated with pre-fire P-J woodland canopy structure, soil water content, infiltration, and revegetation success. One year after the fire, soil water repellency was found to extend just beyond the canopy edge, while subcritical water repellency extended a full canopy radius beyond the canopy edge. Water repellency in this zone was still strong two years after the fire. Where soil water repellency was present K(h), SWC, and vegetation recovery were significantly lower than where soil water repellency was not present. Soil water content, infiltration, and revegetation success were most reduced where water repellency was detected through WDPT's, but were also decreased to a lesser extent on soils with subcritical soil water repellency. Consequently, the severity and extent of soil water repellency may significantly impair post-fire reseeding efforts by limiting seedling establishment of seeded species, and increasing opportunities for invasion by annual weeds, such as *B. tectorum*, which can establish on the resource-rich woody plant copses after soil water repellency has diminished (Davis et al., 2000).

There is a need for innovative management tools and practices that assist in the monitoring and treatment of post-fire P-J woodlands. Based on the strong relation between soil water repellency and pre-burn canopy cover, analysis of remotely-sensed imagery appears to be an effective method for scaling up the estimations of the spatial distribution of water repellent soils to the fire boundary scale and allowing a more accurate assessment of the extent of water repellency and its severity. While the GIS modeling concept proposed in this study for mapping soil water repellency has merit, the approaches proposed require further refinement and testing.

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TABLES

Table 1. Correlation matrix between distance from tree, water repellency (WR) variables, soil water content (SWC) sampled in 2008, and correlation between these same variables plus unsaturated hydraulic conductivity, measured with water $K(h^w)$ and wetting agent $K(h^s)$, and plant density and cover with and without *Nicotiana attenuata* (*N. attenuate*) sampled in 2009. Only significant (P < 0.05) correlation coefficients (r) are shown. Correlations significant at P < 0.0001 are in bold. Non-significant correlations are denoted by 'ns'.

Summer 2008

		Water repellent depth				Infiltration	
Variable	WDPT	Min.	Max.	Thickness	SWC	$K(h^w)$	$K(h^s)$
Dist. from tree	**-0.60**	**-0.69**	**-0.84**	**-0.83**	**0.75**	**0.66**	**-0.73**
WDPT		**0.52**	**0.68**	**0.69**	**-0.50**	**-0.43**	**0.62**
Min. WR			**0.85**	**0.71**	**-0.66**	**-0.54**	**0.53**
Max. WR				**0.98**	**-0.70**	**-0.66**	**0.71**
WR thickness					**-0.66**	**-0.65**	**0.72**
SWC						**0.61**	**-0.60**
$K(h^w)$							**-0.49**

Summer 2009

		Water repellent depth				Infiltration		Vegetation		
Variable	WDPT	Min.	Max.	Thickness	SWC	$K(h^w)$	$K(h^s)$	Density	Cover	Cover w/o *N. attenuata*
Dist. from tree	**-0.46**	**-0.56**	**-0.84**	**-0.81**	**0.70**	**0.73**	-0.33	**0.72**	ns	**0.57**
WDPT		**0.40**	**0.43**	**0.37**	**-0.44**	**-0.40**	0.26	**-0.44**	ns	-0.34
Min. WR			**0.70**	**0.44**	**-0.52**	**-0.48**	0.28	**-0.53**	ns	**-0.38**
Max. WR				**0.95**	**-0.73**	**-0.62**	0.30	**-0.69**	ns	**-0.46**
WR thickness					**-0.69**	**-0.57**	0.25	**-0.63**	ns	**-0.41**
SWC						**0.50**	-0.35	**0.66**	ns	**0.45**
$K(h^w)$							-0.35	**0.71**	ns	**0.45**
$K(h^s)$								**-0.47**	ns	**-0.39**
Veg. density									ns	**0.62**
Veg. cover										0.31

FIGURES

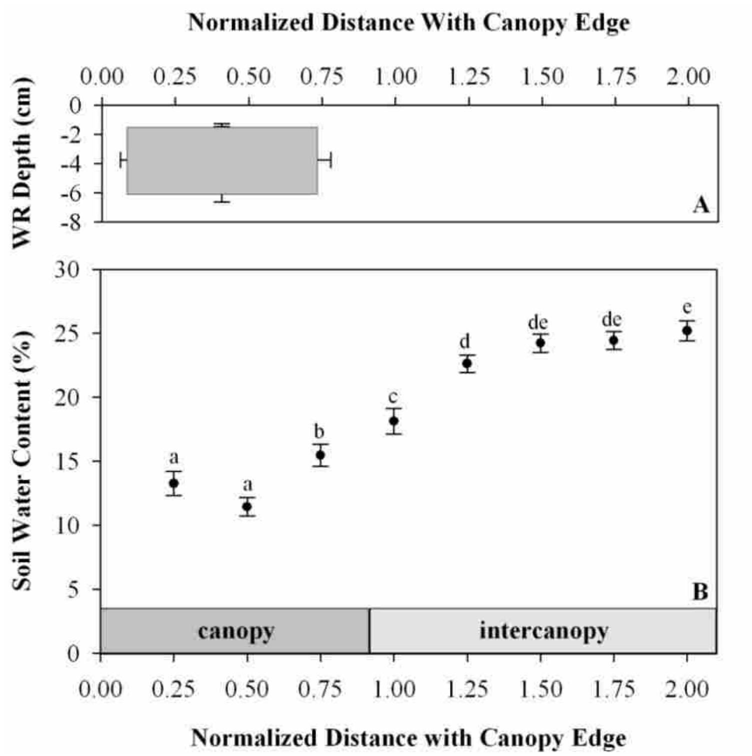

Fig. 1. **A.** Average extent and standard error of soil water repellency layer (WR) measured along radial line transects from the trees bolus to 1 canopy radius past the canopy edge. Along the *y* axis, average depth to the WR layer, and maximum depth of the WR soil layer, measured in a soil pit dug halfway between the trees bolus and the burned canopy edge. **B.** Mean soil water content and standard error from the same transects. Measurements were normalized with respect to canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into quartiles using 0.25 canopy radius.

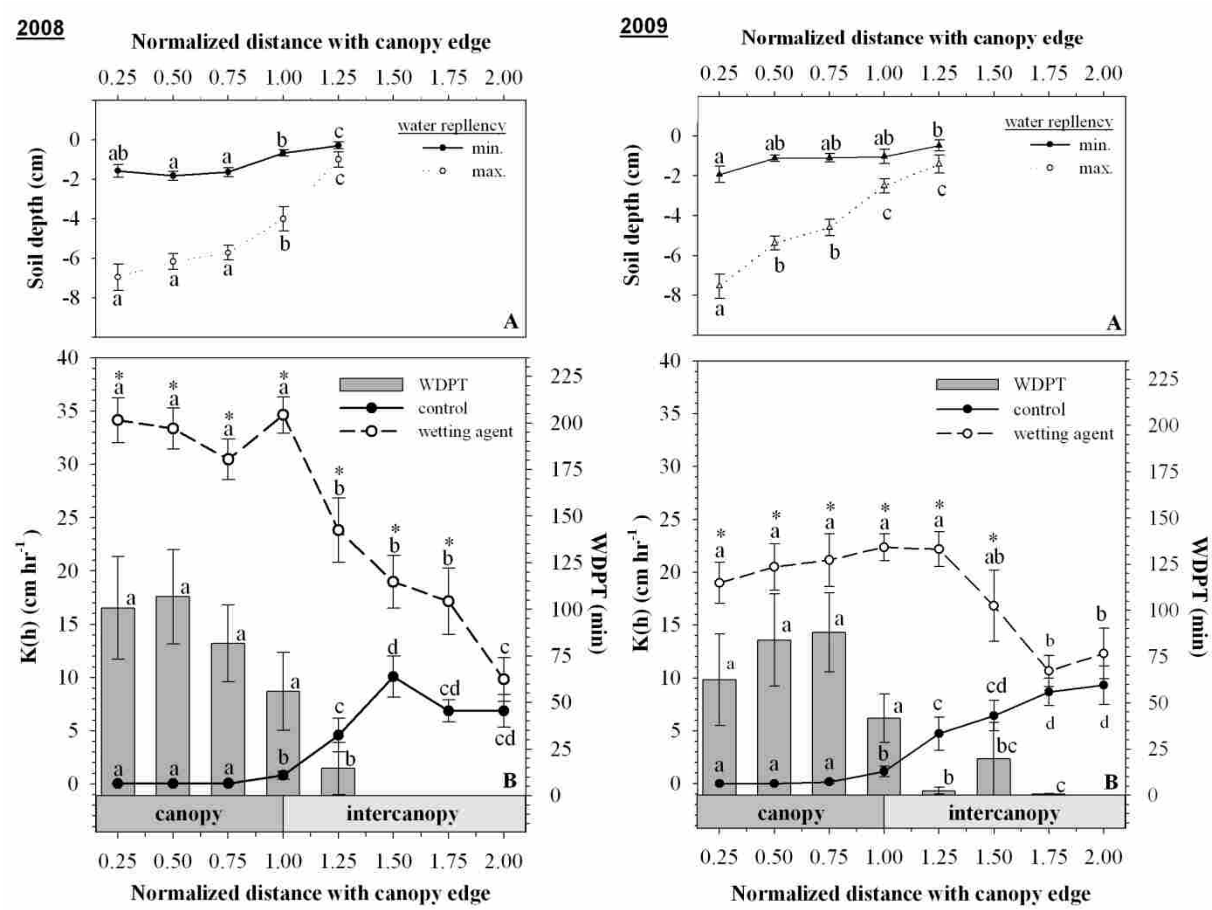

Fig. 2. Results of 2008 and 2009 summer sampling periods. **A.** Depth to (min), and maximum depth (max) of the water repellent layer. **B.** Water repellence severity measured through water drop penetration time (WDPT) tests. Unsaturated hydraulic conductivity, measured with water ($K(h^w)$) and wetting agent ($K(h^s)$). Measurements were normalized with respect to canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into quartiles using 0.25 canopy radius. All results in the figure are presented as mean and associated standard errors. Points with different letters are significantly different ($p < 0.05$). Asterisks indicate significant difference between $K(h^w)$ and $K(h^s)$.

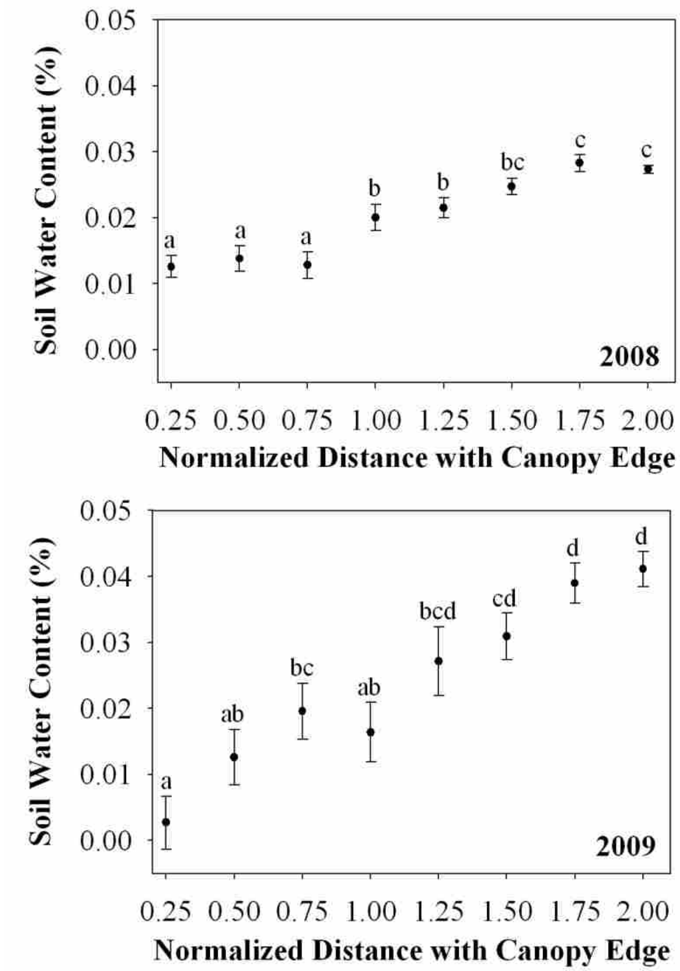

Fig. 3. Soil water content (SWC) measured in 2008 and 2009 every 30 cm along radial line transects from the tree bolus to 1 canopy radius past the burned canopy edge. Data were normalized with respect to canopy width, and grouped into quartiles using 0.25 canopy radius. All results in the figure are presented as mean and associated standard errors. Points with different letters are significantly different ($p < 0.05$).

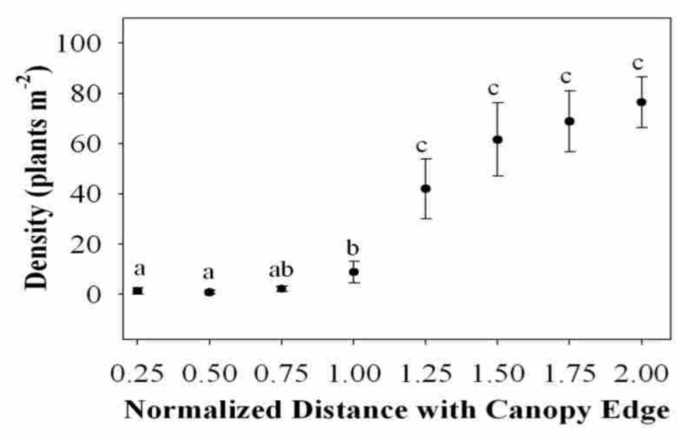

Fig. 4. Total plant density in relation to distance from juniper tree boles. Data were normalized with respect to canopy width, and grouped into quartiles using 0.25 canopy radius. All results in the figure are presented as mean and associated standard errors. Points with different letters are significantly different ($p < 0.05$).

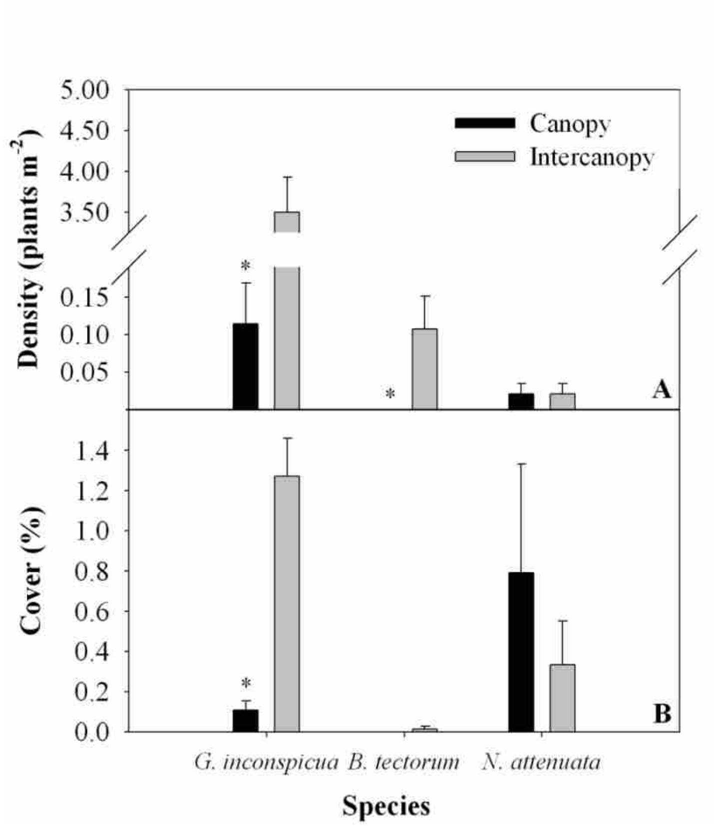

Fig. 5. Average and associated standard error values for canopy and intercanopy (**A**) plant density and (**B**) cover for *Gilia inconspicua,, Bromus tectorum,* and *Nicotiana attenuata* by species. Asterisks indicate significant differences ($p < 0.05$) between canopy and intercanopy values.

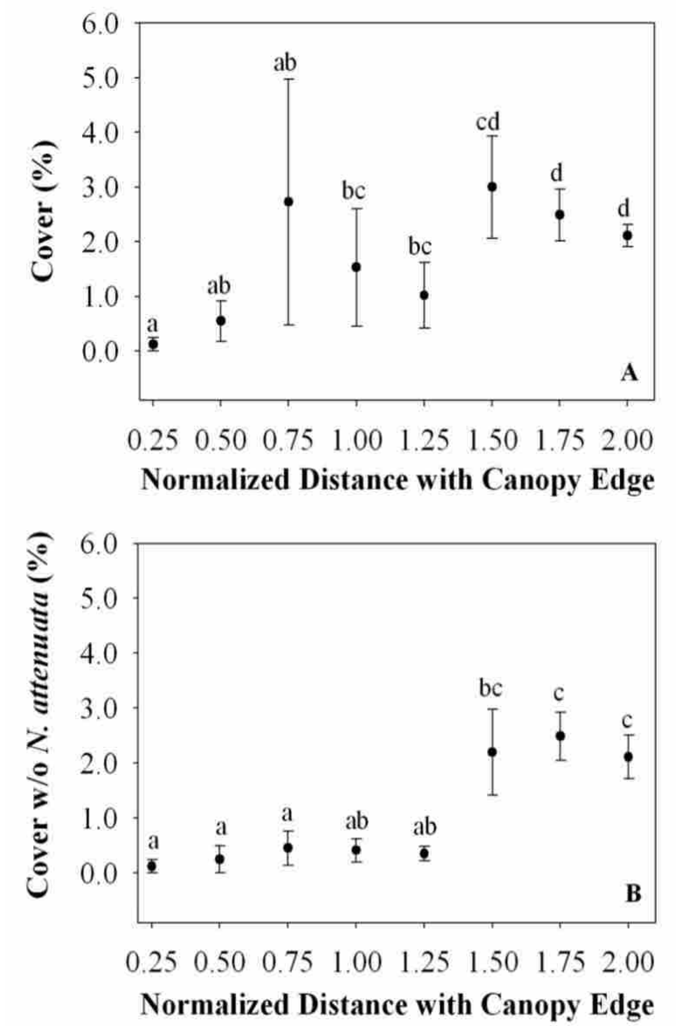

Fig. 6. Vegetation cover data in relation to distance from juniper tree boles with and without *Nicotiana attenuata*. Data were normalized with respect to canopy width, and grouped into quartiles using 0.25 canopy radius. All results in the figure are presented as mean and associated standard errors. Points with different letters are significantly different ($p < 0.05$).

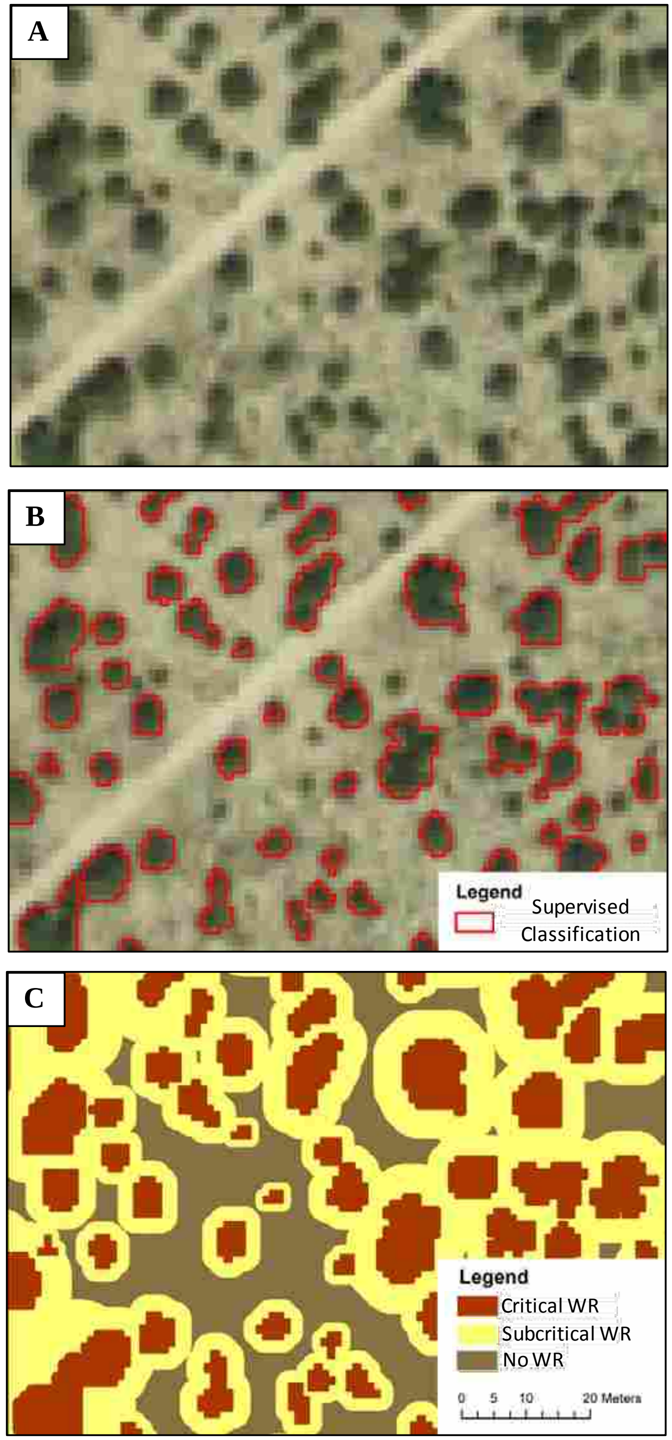

Fig. 7. A. Example of the aerial photography used in this study, **B.** extraction of tree cover using a supervised classification, and **C.** estimate of the percentage of the landscape influenced by critical and subcritical water repellency (WR).

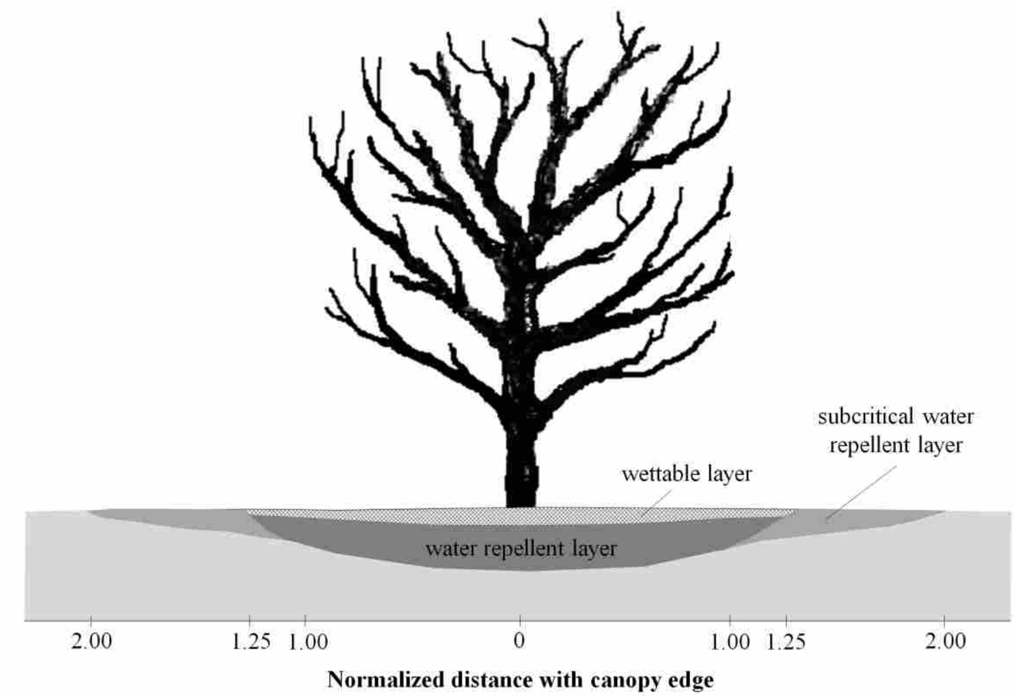

Fig. 8. Schematic diagram of a burned juniper tree canopy, showing areas of water repellent soil and subcritical water repellent soil.

Chapter 4: Impact of Alkylpolyglycoside-ethylene oxide/propylene oxide block copolymers on establishment of *Pseudoroegneria spicata* and *Agropyron cristatum* grown in water repellent soil

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ABSTRACT

Despite post-fire reseeding efforts, piñon-juniper (*Pinus-Juniperus*) woodlands often become invaded by annual weeds that out-compete native species, degrade ecological processes, and modify natural fire patterns. In order to develop successful restoration approaches, we need to understand the mechanisms that impair vegetation recovery in these ecosystems. The development or enhancement of soil water repellency (WR) commonly occurs after a fire. However, the influence of this soil condition on revegetation success is poorly understood. Our objective was to quantify the influence of WR on soil hydrologic properties, seedling emergence, and plant growth in a glasshouse study using soil cores obtained from the subcanopy of burned juniper trees. Treatments applied to soil cores included seeding *Pseudoroegneria spicata* or *Agropyron cristatum* and growing them under high and low water regimes (high = 1.2 cm daily, low = 1.2 cm every 5 days) and either with or without additions of alkylpolyglycoside-ethylene oxide/propylene oxide block copolymers. Soil water repellency reduced seedling emergence and seedling establishment by decreasing soil moisture availability through: redirecting precipitation down-slope, decreasing soil moisture storage capacity, and disconnecting soil surface layers from underlying moisture reserves. Wetting-agents improved ecohydrologic properties required for plant growth by overcoming soil water repellency and increasing the amount and duration of available water for seed germination and seedling survival. Seedling densities under the low watering regime were on average 292% higher than untreated soils. In semi-arid environments, soil WR may act as a temporal ecological threshold impairing establishment of desired species within the first few years after a fire, enabling subsequent weed invasion after WR has diminished.

Keywords: hydrophobicity, pinyon-juniper, restoration, revegetation, surfactants, water repellency, wetting agents, wildfire, weed suppression

INTRODUCTION

The pronounced expansion of woody vegetation in semi-arid ecosystems has been observed globally (Van Auken 2000; Briggs et al. 2002; Huxman et al. 2005; Breshears 2006). Proposed primary causal factors include high intensity grazing, fire suppression (Bragg and Hulbert 1976; Heisler et al. 2003), increased atmospheric CO_2 concentrations (Mayeux et al. 1991; Johnson et al. 1993), and climate change (West 1999; Miller and Tausch 2001; Romme et al. 2009). In the western United States, the range of expansion and stand infilling by piñon (*Pinus*) and juniper (*Juniperus*) (P-J) species into grassland and sagebrush communities constitutes one of the greatest afforestations of our time (Miller et al. 2008). Since European settlement of the Western US, these species have expanded their range to more than 40 million hectares (Romme et al. 2009). This ecosystem shift has resulted in negative impacts to soil resources, plant community structure and composition, forage quality and quantity, water and nutrient cycles, wildlife habitat, and biodiversity (Miller et al. 2008). As P-J woodlands mature, increased fuel loads and canopy cover can lead to large scale, high intensity crown-fires (Miller and Tausch 2001; Miller et al. 2008). After a fire, the ability of a P-J dominated ecosystem to recover depends on the extent to which physical and biological processes controlling ecosystem function have been altered, both prior to and as result of the fire (Miller and Tausch 2001; Briske et al. 2005).

When ecological thresholds are crossed in these systems, the recovery of desirable species may not be possible without direct intervention. Areas associated with P-J vegetation often remain bare for one or more years after fire. If desirable perennial species are unable to establish the first year following fire, sites can transition into a secondary state of weed dominance, which then promotes more frequent fire return intervals and decreased native plant establishment, further impairing vital ecosystem functions (Young and Evans 1978; Billings 1990).

One factor that can restore natural processes and prevent movement toward undesirable thresholds is the successful establishment of desirable vegetation within the first year after a fire. In the past, land managers have typically selected introduced species for post-fire rehabilitation such as crested wheatgrass (*Agropyron cristatum (L.) Gaertn*.) and forage kochia (*Bassia prostrata (L.) A.J. Scott*) (e.g. Thompson et al. 2006). These species often have more consistent establishment, lower costs, better weed competition, and improved livestock forage quality. Currently, fire rehabilitation programs are increasing the use of native plant materials in place of introduced species in an effort to reinstate ecosystem processes and improve species diversity after a fire (Walker and Shaw 2005; Thompson et al. 2006); however, these species are costly and establishment success is typically less than desirable (Roundy et al. 1997). Therefore, the use of native species in post-fire restoration increases project costs, while decreasing the likelihood of successfully-establishing a functioning community. These issues reduce the desire of land managers to include native plant materials in fire rehabilitation treatments.

To improve the success of reseeding efforts, several mechanical and non-mechanical treatments have been proposed with varying degrees of effectiveness. For example, aerial reseeding followed by anchor chaining is commonly practiced for post-fire rehabilitation of P-J woodlands (Ott et al. 2003). Although this form of mechanical treatment has been shown to be successful in many situations, the additional disturbance may increase risk of soil erosion by wind and water (Wiedemann 1987; Evans and Young 1987; Miller 2009). Furthermore, economic, cultural, and topographic constraints (i.e. soils are too rocky or steep) prevent the use of this mechanical treatment on a significant portion of the landscape.

When restoration practices fail, ecological resilience is compromised, and soil loss, weed invasion, and other factors act as triggers that initiate feedback shifts that carry a site across ecological thresholds to undesirable alternate stable states. Land managers throughout the Intermountain West are calling for new techniques that improve establishment of native plant materials to restore habitats lost to wildfire and prevent subsequent weed dominance.

In order to develop successful post-fire restoration approaches, it is critical that the mechanisms which impair vegetation recovery after a fire and the conditions that developed prior to the fire which resulted in the crossing of ecological thresholds are understood. If the state of an individual site is known in relation to ecological thresholds and possible transitions to other states, capital can be correctly allocated to sites in transition, in order to promote the system's natural ability to recover. Furthermore, an understanding of the mechanisms that prevent post-fire recovery will allow the development of resilience-based approaches that promote recovery of post-fire ecosystem process and function (Briske et al. 2008).

Hydrophobicity, or soil water repellency, is one factor that may significantly limit post-fire recovery in P-J systems and promote subsequent weed domination. Soil water repellency is commonly found in arid and semi-arid ecosystems and its presence has been documented within P-J woodlands (Roundy et al. 1978; Jaramillo et al. 2000; Rau et al. 2005; Madsen et al. 2008 and chapter 3). In chapter 3 we showed that post-fire patterns of soil water repellency were highly correlated with, decreased soil water content, infiltration, and revegetation success. We hypothesize that post-fire WR acts as a temporal ecological threshold by impairing establishment of desired species within the first few years after a fire, which then leaves resources available for weed invasion after WR has diminished. Better knowledge of WR in P-J ecosystems is necessary to guide management actions as these woodlands continue to encroach, infill, and mature throughout their adaptable range (Miller et al. 2008).

Restoration approaches which focus on ameliorating WR could potentially improve the success of native plant materials in post-fire reseeding efforts while simultaneously decreasing runoff and soil erosion, and preventing weed domination. Use of commercially available surface active agents (wetting-agents or surfactants) may provide an alternative post-fire restoration approach where WR inhibits site recovery. A wide variety of ionic and nonionic wetting-agents are produced commercially, ranging from simple dish soaps to sophisticated polymers chemically engineered to overcome WR. Wetting-agents are generally organic molecules that are amphiphilic (hydrophobic tails and hydrophilic heads). While wetting agents have different modes of action, in the case of soil applications the hydrophobic tail of the wetting-agent chemically bonds to the non-polar water repellent coating on the soil particle, while the hydrophilic head of the molecule attracts water molecules, thus rendering the soil wettable.

Various small plot, post-fire research projects located in the mountains of southern California have shown that the application of wetting-agents after a fire can reduce soil erosion and improve vegetation establishment (e.g. Osborn et al. 1964; Pelishek et al. 1964; Osborn et al. 1967; Krammes and Osborn 1969; Debano et al. 1974). These studies suggest that wetting-agent applications can be a successful post-fire treatment. While wetting-agents have not been used in wildland systems since the 1970's, they have been extensively used and further developed within various aspects of the agricultural industry, with most applications in turf grass systems (e.g. Cisar et al. 2000; Kostka et al., 2008). Subsequently, the effectiveness of these chemicals in overcoming soil WR has been improved (Cisar et al. 2000; Kostka 2000; Kostka and Bially 2005). The development of these wetting-agents may provide an innovative approach for alleviating the effects of WR on germination and establishment of native vegetation species, thus allowing them to better compete with invasive annual weed species such as cheatgrass (*Bromus tectorum* L.).

The primary objectives of this research were to quantify within a glasshouse setting: 1) the extent that soil water repellency influences emergence and growth of the non-native bunchgrass crested wheatgrass (*Agropyron cristatum* (L.) Gaertn., and native bunchgrass, bluebunch wheatgrass (*Pseudoroegneria spicata (Pursh) A. Löve*), both of which are commonly seeded for fire rehabilitation, in the Intermountain West, USA; and 2) determine the effects of the newly developed non-ionic wetting-agent “Soil Penetrant”(Aquatrols Inc., Paulsboro, NJ) on WR and seedling growth to assess its potential use in wildfire rehabilitation of P-J ecosystems.

METHODS

Study area

Soil obtained for this study was collected within the boundaries of Utah’s largest wildfire on record (145,000 ha), the 2007 Milford Flat wildfire. Soil was collected one year after the fire from a predominantly west- facing site 13.7 km NW of Milford, UT, USA (337415 E, 4255901 N, Zone 12) at the base of the Mineral Mountain Range (elevation 1847 m). Soils are classified as coarse sandy loam, mixed, mesic Aridic Haploxerolls (3-10% slope). Mean annual precipitation at the site is 370 mm (PRISM Climate Group 2009). Prior to the fire, the vegetation community was a Phase III, P-J woodland (i.e. “trees are the dominate vegetation and primary plant layer influencing ecological processes on the site”; Miller et al. 2005) with Utah juniper (*Juniperus osteosperma* (Torr.) Little) and singleleaf piñon (*Pinus monophylla Torr. & Frém.*).

At the time of collection, the soil remained almost completely bare of live vegetation. Madsen et al. (Chapter 3) found that the average water drop penetration time (WDPT) (Krammes and DeBano 1965) under the subcanopy of burned P-J trees was 1.36±0.19 hrs. The mean depth of the WR zone was (4.80±0.51 cm), with average minimum and maximum WR depths of 1.40±0.12 cm and 6.1±0.53 cm, respectively.

Study design

Soil cores were collected in soil cylinders (30.5 cm diameter by 36-cm deep) made of polyvinyl chloride (PVC), which were pressed into the soil with a hydraulically-operated front end loader bucket on a tractor. To minimize soil compaction, the end of the tube was sharpened before pressing into the soil. Cores were modified for use as growing pots by fastening a woven landscape fabric to the bottom of the soil core. As P-J woodlands typically occur on sloping terrain and the influence of soil WR can be more pronounced on a slope, all pots were placed on a 15° angle, similar to methods described by Osborn et al. (1967). To allow for drainage at the soil surface, pots were fitted with a runoff spout 19.1 mm in diameter, placed in the pot so the bottom of the spout was at the top of the WR layer (Fig.1). Pebbles were placed in front of the spout to prevent seed and soil loss.

Treatments included soil cores treated with and without wetting-agent, two watering regimes, and two seeded species, with all combinations arranged in a randomized block split-plot design, with three soil core replicates per block, and five blocks in the study (2 soil treatments x 2 watering regimes x 2 species x 3 core-replicates x 5 blocks = 120 soil cores in the study). Each pot was seeded with 35 seeds of either crested or bluebunch wheatgrass. The total germination of each species was tested in 13 cm diameter petri-dishes using 3 replications of 50 seeds per species, and was found to be 90% for crested wheatgrass and bluebunch wheatgrass. During the first watering, 0.012 ml cm^{-2} of "Soil Penetrant" (Aquatrols Corp., Paulsboro, NJ), which is a nonionic wetting-agent composed of a blend of alkylpolyglycoside (APG) and ethylene oxide/propylene oxide (EO/PO) block copolymers, was applied to half the soil cores. In preliminary tests, this wetting-agent concentration was required to allow complete wetting of the soil column.

Pots were watered by running rainfall simulators with the bottom of the simulator 40 cm above the soil surface (Fig.1). Individual rainfall simulators were designed to water one pot at a time, constructed from seven liter buckets, which had a 25.4 cm radius bottom, and 50 drip tubes (10 mm long, with an inside diameter of 0.864 mm and wall thickness of 0.305 mm), to drain the water. The rate of flow from the bucket was controlled by adjusting the head pressure using a Mariotte tube (4.8 mm diameter), which slid within a bored rubber stopper attached to the top of the bucket. To start and stop the flow of water from the rainfall simulator, surgical tubing and a clamp were placed at the top of the Mariotte tube.

Pots were watered under either a low or a high watering regime. The low watering regime was designed to replicate spring-like conditions, with periods of adequate soil moisture, followed by intermittent periods of no precipitation. The high water regime was designed so the seedlings would not be stressed due to a lack of soil moisture. At each watering a total of 0.62 cm (400 ml) of water was delivered at a rate of 3.0 cm hr^{-1}. The low watering treatment consisted of watering daily for the first 4 days, to insure seed germination, then once every 5 days. Pots were also watered daily on days 20-24 to see if seeds not yet germinated would emerge. Under the high watering regime, pots were watered daily throughout the project.

Measurements

Three of the five blocks in the study were randomly chosen to collect runoff. To measure runoff, a catchment tube made of 4.5-cm-diameter thin-wall PVC cylinders and cap (Geoprobe, Salina, KS) was hung just below the runoff spot of each pot (Fig.1). For each different watering regime and soil treatment, four pots were randomly selected for soil water content measurements. At the 1-3 cm soil depth, soil water content was recorded continuously with EC-5 Soil Moisture Sensors in conjunction with Em5b data loggers (Decagon Devices, Pullman, WA). To relate water content to water potential, moisture release curves were developed for this soil type using the WP4 dewpoint meter (Decagon Devices, Pullman, WA). For all blocks, the number of live seedlings was recorded every 2 days throughout the experiment. Plants were harvested 48 days after seeding; below-ground and above-ground biomass was measured separately after drying at 65 °C for 72 hrs.

Data analysis

Data were analyzed using SYSTAT 12 (Systat Software Inc. Chicago, IL), with significance determined at $P < 0.05$ level. Mixed model analysis was used to analyze runoff, soil water content, seedling density, above-ground biomass, and below-ground biomass. Blocks were considered random, while species, watering regimes, and soil treatments were considered fixed factors. Runoff and soil water content were analyzed as repeated measures. Because soil water content was recorded continuously, analysis was performed on values at the time of watering (i.e. peak SWC), and 4 days after watering (i.e. trough SWC). Treatments not found to be significant were combined. For treatments found to affect the response variables, mean values of the response variables were separated using Tukey's Honestly-Significant-Difference (HSD) test.

RESULTS

Runoff

Runoff was not significantly influenced by measurement date, species, or watering regime, but was significantly influenced by wetting-agent treatment (Table 1. A). Mean runoff over the course of the study from the untreated control was 21.4% of the water added, while the wetting-agent treatment had only 5.0% runoff (Table 1. B).

At harvest, it was observed that the majority of the control pots still had a band of air-dry soil just below the soil surface that exhibited severe WR (Fig. 2). It is speculated that for the control pots, water that did not runoff from the soil cores infiltrated along the sides of the pot, until it was below the WR zone. In contrast, wetting-agent treated soils appeared to allow for an even wetting of the entire soil core (Fig. 2).

Soil water content

Soil water content was affected by watering regime and wetting-agent treatment (Table 1.). Under the low watering regime, wetting-agent treated soil had higher peak soil water content at the time of watering, and maintained elevated values in-between watering events, in relationship to the control. After the second continued watering period, soil water content was still high in the wetting-agent treated soils compared to the control. However, during this period soils did not dry down as rapidly between watering for both the control and wetting agent treatments. The sustained soil water contents may be attributed to several frontal storms that occurred during this period, which resulted in high glasshouse humidity levels and reduced soil evaporation rates. Under the high watering regime, soil water content was statistically similar, although the peaks and troughs on average were higher for wetting-agent treated soil.

Density

Seedling survival was influenced by watering regime, wetting-agent application, and species (Table 2). However, relative seedling density normalized by percent of germinable seeds did not differ by species (Table 2). Under the low water regime and within the control pots, seedling density peaked at about 10 days (Fig. 3). Between day 10 to shortly after we reinitiated daily watering (day 20), seedling densities of the control pots dropped by 72.3%. Wetting-agent treated pots had a peaked at day 14, with seedling densities 268 percentage points higher than the control peak densities. Unlike the control pots, wetting-agent treated pots under the low water regime had relatively few plants desiccate before the next daily watering period, with a drop in seedling density of only 9.2%.

Daily watering on days 20-24 further increased seedling densities of control and wetting-agent treatments as seeds germinated that had not germinated previously under the low water regime. The control increased in density by 546 percentage points, while the wetting-agent treatment increased 30.9 percentage points (Fig. 3). With this new cohort of seedlings, it was expected that there would be a similar response compared to seedlings that emerged at the start of the study. However, as explained previously, high humidity levels in the glasshouse most likely inhibited the loss of soil moisture and subsequent seedling desiccation, particularly in the control soils. Despite glasshouse conditions with abnormally high humidity levels, at the end of the experiment under the low watering regime, wetting-agent treated pots had significantly higher seedling establishment, with 292% higher seedling survival in comparison to the control pots (i.e. average low water plant density was 112.1±12.2 and 439.1±39.5 plants m^{-2} for control and wetting-agent treated pots, respectively).

Under the high water regime, control pot seedling densities steadily increased over the course of the experiment, with seedling densities similar to wetting-agent treated soils under the low watering regime (Fig. 3). Wetting-agent treated pots under the high regime also had statistically higher seedling densities than the control pots, with 49.6% higher seedling survival (i.e. average high water plant density was 474.1±20.7 and 708.6±33.7 plants m^{-2} for control and wetting-agent treated pots, respectively).

Biomass

Total above-ground biomass was influenced by watering regime, wetting-agent application, and species (Table 2). Pots treated with wetting-agent and under the low water regime had above-ground biomass 690% and 722% greater than the control, for crested wheatgrass and bluebunch wheatgrass respectively (Fig. 4). Above-ground biomass of wetting-agent treated pots for both species, under the low watering regime was statistically similar to the control under the high watering regime. Under the high watering regime, biomass of seedlings in the wetting-agent treated pots was statistically higher than seedlings in the control, with above-ground biomass 50% and 66% greater than the control for crested wheatgrass and bluebunch wheatgrass, respectively (Fig. 4). However, under the high watering regime biomass of crested wheatgrass was similar to that of bluebunch wheatgrass grown in wetting-agent treated soil.

Below-ground biomass was influenced by watering regime and wetting-agent application, but unlike above-ground biomass it did not differ by species (Table 2). Of all the response variables measured in this study, below-ground biomass showed the greatest increase with wetting-agent treatment. Pots treated with wetting-agent under the low water regime had below-ground biomass 1056% and 1196%, greater than the control, for crested wheatgrass and bluebunch wheatgrass, respectively.

Similar to above-ground biomass, wetting-agent treated pots under the low watering regime had statistically similar above ground biomass as control treatments under the high watering regime, but statistically less biomass than wetting- agent treated pots under the higher watering regime. Under the high water regime, above-ground biomass in the wetting-agent pots was greater than the control by 119%, and 127%, for crested wheatgrass and bluebunch wheatgrass, respectively. While harvesting the control pots, we observed that seedling roots generally did not grow through the WR layer, but grew along the sides of the soil pot to avoid the WR layer. In contrast, roots were evenly distributed throughout the pot of the wetting-agent treated soil (Fig. 2).

Greater above-ground biomass for crested wheatgrass in comparison to bluebunch wheatgrass was, in part, most likely due to greater germination and seedling density. Analysis of above-ground biomass on a per-plant basis indicated that these species generally performed similarly (Table 2). Under the low watering regime, average per-plant above ground biomass was 111.6 percentage points higher for plants in wetting-agent treated pots than those in the control pots. Per-plant above-ground biomass grown in wetting-agent treated pots under the low watering regime was similar to that of plants grown in the high watering regime treatment with or without wetting-agent (Fig. 5). These results show in part that the wetting-agent treatment under the low watering regime and control and wetting-agent treatments under the high watering regime had greater biomass than controls; however, it is important to note that the age of the plants being compared are not the same, because the control pots had a significant increase in seedling establishment halfway through the study (Fig. 3).

Below-ground biomass on a per-plant basis was 224.0% higher for plants grown in wetting-agent treated pots under the low watering regime. Control pots under the higher watering regime were similar to wetting-agent treated pots under the low watering regime, while both these treatments were statistically less than plants gown in wetting-agent pots under the higher watering regime.

The ratio of above and below-ground biomass was influenced by watering regime and wetting-agent application but not species. Fig. 6 shows the mean ratio of above and below-ground biomass for the different treatment combinations. Ratios greater than one indicate higher above-ground biomass in relationship to below-ground biomass. Under the low watering regime, the ratio of above and below-ground biomass for the control pots was statistically higher than wetting-agent treated pots by 138.6%. Biomass of plants grown in wetting-agent treated pots under the low watering regime was similar to those grown in either treatment, under the high watering regime.

DISCUSSION AND CONCLUSIONS

Although this study was conducted under simulated field conditions in a glasshouse, it strongly suggests that within burned P-J woodlands, soil WR can promote runoff and disconnect seeds/seedlings from the underlying soil moisture reserves, thereby leaving the seed/seedling without adequate soil moisture. It is speculated that field conditions would likely have resulted in an even greater difference is seedling survival. Potentially the cycle of seedling emergence and desiccation may be frequent in the field, resulting in a loss of residual or aerially-seeded seeds from the seed bank. It is hypothesized that soil WR acts as a temporal ecological threshold, impairing establishment of desired species within the first few years after fire, leaving resources available for weed invasion after WR has diminished.

These results also provide evidence that wetting-agents can ameliorate post-fire WR and subsequently help restore ecohydrologic function in conjunction with reseeding efforts. Application of wetting-agents in this study significantly decreased water runoff and increased the amount of available soil moisture, which increased plant density, and above and below ground biomass.

Results of this study are consistent with previous studies within the California chaparral which showed that wetting-agents significantly improving seedling densities on post-fire WR soil (e.g. Osborn et al. 1964; Pelishek et al. 1964; Osborn et al. 1967; Krammes and Osborn 1969; Debano et al. 1974). This research, along with previous studies in other ecosystems, provides evidence that this technology should be further field-tested in wildland systems impaired by post-fire soil WR. For example, where public structures or water systems are in danger of degradation from runoff and soil erosion, wetting-agents could be used to improve infiltration rates and stabilize soils, preventing costly physical and environmental damage. Another promising and innovative approach for using wetting-agents may be in coating seeds with them to alleviate the effects of WR on germination and establishment of native vegetation species, thus allowing them to better compete with invasive annual weeds. Further research could be performed in applying wetting-agents by aircraft in a granular form or directly coated on the seed itself, providing a cost effective post-fire restoration treatment.

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TABLES

Table 1. A. Mixed-model analysis indicating significance of water regime and wetting agent treatment on runoff, soil water content just after watering (SWC: peak), and four days after watering (SWC: trough). **B.** Pair-wise comparisons showing mean and associated standard error for the response variables that were found to be significant.

A.

Hydrologic Response

Effect variables	Runoff		SWC: peak		SWC: trough	
	F	*P*	*F*	*P*	*F*	*P*
Water regime	[illegible]	[illegible]	[illegible]	*<0.001*	[illegible]	*<0.001*
Wetting Agent	[illegible]	*<0.001*	[illegible]	[illegible]	[illegible]	*<0.001*
Species	[illegible]	[illegible]	-	-	-	-

B.

Pair-wise comparisons

	Runoff	SWC: peak	SWC: trough
Low water + control	[illegible]	[illegible]	[illegible]
Low water + WA	[illegible]	[illegible]	[illegible]
High water + control	[illegible]	[illegible]	[illegible]
High water + WA	[illegible]	[illegible]	[illegible]

[illegible]

Table 2. Mixed-model analysis of crested and bluebunch wheatgrass seedling responses to water regime and wetting agent treatment in water repellent soils collected from underneath burned juniper trees.

Vegetation response

Response variables	Water regime		Wetting agent		Species	
	F	*P*	*F*	*P*	*F*	*P*
Seedling survival	[illegible]	*<0.001*	[illegible]	*<0.001*	4.9	*0.034*
Survival of germinable seeds	[illegible]	*<0.001*	[illegible]	*<0.001*	[illegible]	[illegible]
Above-ground biomass	[illegible]	*<0.001*	[illegible]	*<0.001*	[illegible]	*0.002*
Below-ground biomass	82.6	*<0.001*	[illegible]	*<0.001*	2.4	[illegible]
Above-ground biomass per plant	[illegible]	*<0.001*	[illegible]	*0.002*	[illegible]	[illegible]
Below-ground biomass per plant	56.5	*<0.001*	[illegible]	*<0.001*	[illegible]	0.510
Above:below ratio	12.2	*0.001*	[illegible]	*0.002*	[illegible]	[illegible]

FIGURES

A.

B.

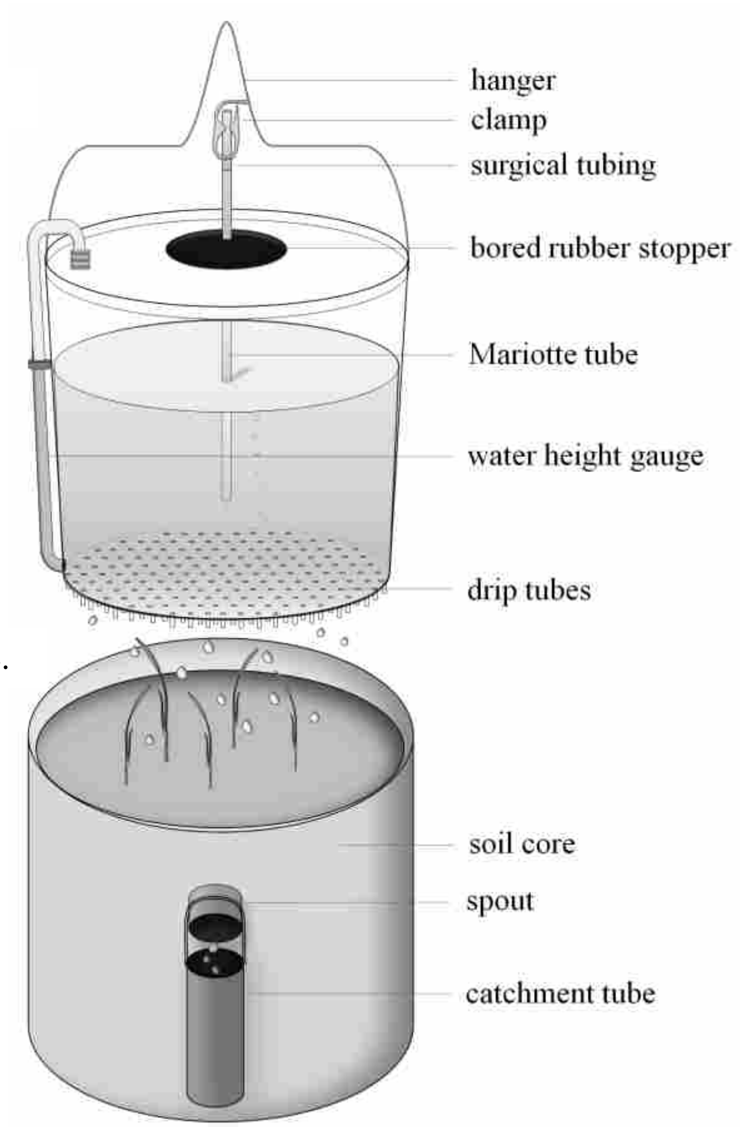

Fig.1 A. Diagram of rainfall simulator, and **B.** soil core modified for use as a growing pot, and attached runoff catchment tube.

Fig. 2. Aerial view and cross section photo's of Bluebunch wheatgrass seedlings grown under a low water regime, on water repellent soil, and soil with water repellency reduced by addition of a wetting agent (WA).

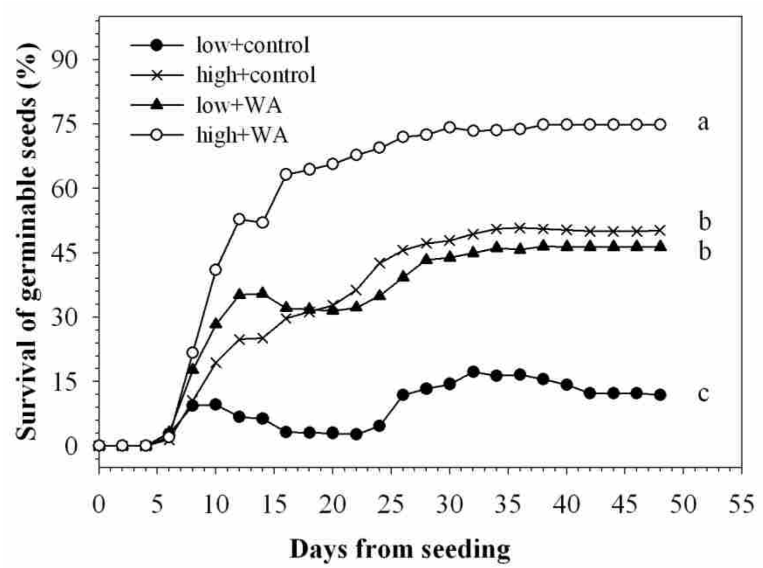

Fig. 3. Combined results for crested wheatgrass and bluebunch wheatgrass seedling densities over the course of the experiment, with results normalized by total germination for pots watered under a low or high watering regime, treated with or without wetting agent (WA). Significant differences ($P < 0.05$) at the end of the experiment are shown by unique letters.

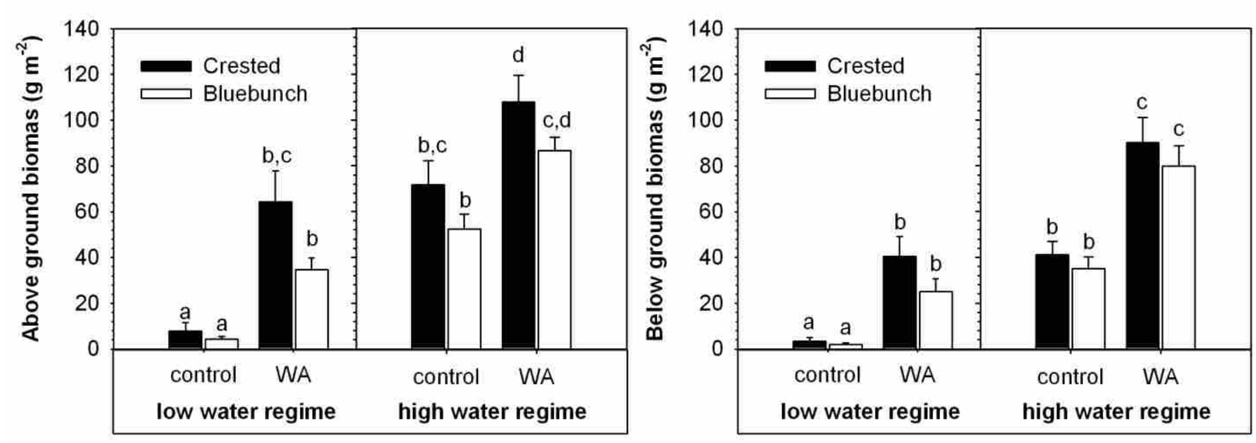

Fig. 4. Above and below ground biomass of crested wheatgrass and bluebunch wheatgrass grown on water-repellent soil treated with or without wetting agent (WA), under high and low watering regimes. Significant differences ($P < 0.05$) at the end of the experiment are shown by unique letters.

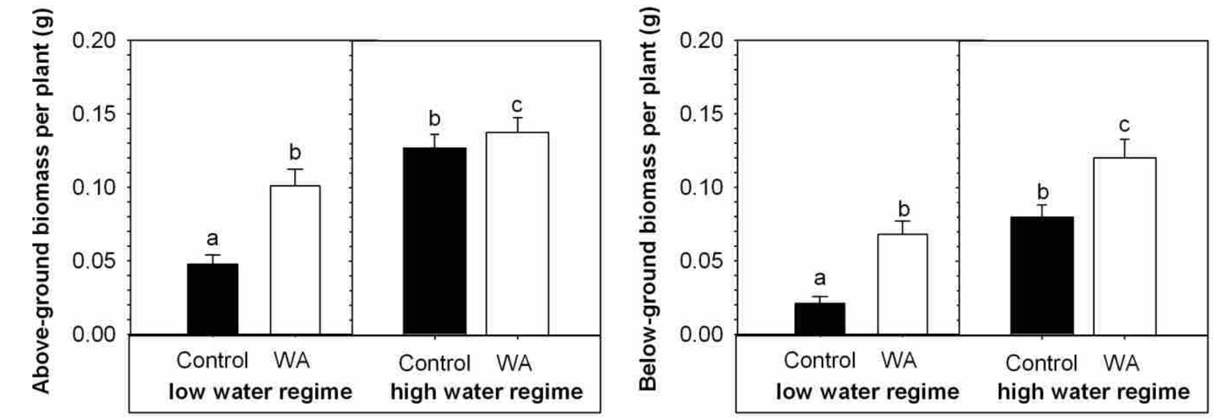

Fig. 5. Combined results for crested wheatgrass and bluebunch wheatgrass for above and below ground biomass on a per-plant basis, grown on water- repellent soil, with and without wetting agent (WA), under high and low watering regimes. Significant differences ($P < 0.05$) at the end of the experiment are shown by unique letters.

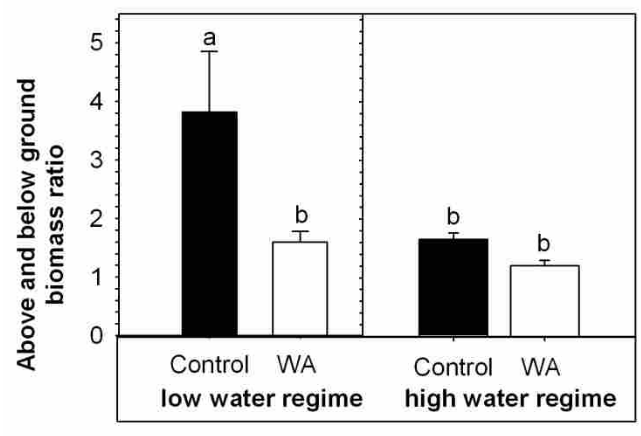

Fig. 6. Combined above and below-ground ratios for crested wheatgrass and bluebunch wheatgrass grown on water-repellent soil, treated with and without wetting agent (WA), under high and low watering regimes. Significant differences ($P < 0.05$) at the end of the experiment are shown by unique letters.

Chapter 5: Comparison of Post-fire Soil Water Repellency Amelioration Strategies on Bluebunch Wheatgrass and Cheatgrass

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ABSTRACT

The development or enhancement of soil water repellency can significantly limit site recovery following wildfire. This study was designed to compare survival and growth of the native plant species bluebunch wheatgrass (*Pseudoroegneria spicata)* to the invasive annual weed cheatgrass (*Bromus tectorum*), and to compare the effectiveness of wetting agents and soil tillage for improving plant survival and biomass production in water-repellent soil. Research was performed in the glasshouse using soil cores obtained from the subcanopy of burned juniper trees. Three treatments plus a control were tested in a randomized split-plot design: (1) control, (2) till, (3) wetting agent, and (4) till + wetting agent. Response variables measured included: soil water content, plant density, above and below-ground biomass, and soil and plant nitrate levels. Overall, response of bluebunch wheatgrass and cheatgrass was similar among treatments. Tilling the soil in general increased soil water content. Wetting agent treatments resulted in significantly higher soil water content than till and control. Seedling density was similar between control and till treatments, while wetting agent treatments produced higher density than either the control or till treatments. By the end of the study, cheatgrass plants growing in soil treated with wetting agent showed signs of nitrogen deficiency. Soil receiving the wetting agent treatments had significantly lower nitrate concentrations. Similarly, cheatgrass nitrate levels grown in soil treated with wetting agent were lower than those from untreated soil. No significant difference in plant nitrate concentration was observed between treatments for bluebunch wheatgrass. This study suggests that cheatgrass and bluebunch wheatgrass are both influenced by soil water repellency. Application of wetting agents promotes bluebunch wheatgrass survival. Further research is merited for determining the implications of water repellency on soil nutrient retention, amelioration through wetting agents and cheatgrass survival.

Keywords: anchor chaining, hydrophobicity, pinyon-juniper, restoration, revegetation, surfactants, water repellency, wetting agents, wildfire, weed suppression

INTRODUCTION

Large-scale catastrophic wildfires are becoming more frequent and severe within rangeland ecosystems of the Intermountain West (Miller and Tausch, 2001). In particular, ecosystems which have been encroached by pinyon-juniper (*Pinus-Juniperus*) (P-J) woodlands over the last 150 years pose a significant challenge to land managers in restoring desired plant communities after a fire. Often these systems become weed dominated, causing significant impacts to rangeland ecological services, including decreased forage production, watershed stability, and water quality (i.e. Arnold et al., 1964; Shinneman, 2006).

After a fire the ability of ecosystems to recover is dependent on the extent to which ecological processes have been altered (Briske et al., 2005). The development or enhancement of soil water repellency is one such alteration that can significantly limit site recovery (e.g. Krammes and Osborn, 1969; see chapter 3). Woody vegetation in arid and semiarid climates facilitates the establishment of a hydrophobic layer in the first few centimeters of the soil profile (i.e. Doerr, et al., 2000; Jaramillo et al., 2000; Madsen et al., 2008). During a fire, heat volatilizes organic substances in the litter and upper soil water repellent layers. These volatilized compounds move downward into the soil, condensing around soil particles in the cool underlying soil layers, resulting in a shallow wettable layer at the soil surface, and an intensified water repellent zone below (DeBano, et al., 1970). The development or enhancement of this water-repellent layer has important implications for revegetation success, runoff, and soil erosion (Doerr et al., 2000). During a rainfall event, water repellency impedes infiltration, leading to rapid saturation of the upper wettable layer. On steep slopes this saturation can enable water, soil, and debris to quickly flow down slope, resulting in extensive soil erosion, overall site degradation, and sediment pollution (DeBano, 1981). As shown in chapter 4, seeds that germinate in the upper wettable soil layer typically desiccate because the water repellent layer disconnects seedling roots from the underlying soil moisture reserves. The lack of seedling establishment can allow for continued soil erosion and provide a window for weed invasion (Young et al., 1976). In light of these effects and the large amount of public capital invested annually on post-fire rehabilitation treatments, it is important that post-fire treatment strategies consider and mitigate the effects of soil water repellency.

Broadcast seeding followed by one-way anchor chaining has been shown to significantly improve establishment of standard aerial-seeded plants, while decreasing weed establishment (Ott et al., 2003). Breaking up soil water repellency after a fire using an anchor chain is thought to be one of the mechanisms responsible for influencing the restoration of P-J systems (Minutes of the Natural Resources, Agriculture and Environment Interim Committee, 1997). While there has been substantial internal knowledge developed over the years by land management personnel, formal studies examining the mechanisms by which anchor chaining improves seedling germination and establishment in the presence of water- repellent soil are lacking. Improving our understanding of how land management techniques influence site recovery in the presence of water- repellent soil will aid the design and implementation of restoration treatments.

Various studies conducted in the late 60' and early 70's, in southern California have shown that the application of wetting agents (surfactants) after a fire can reduce soil erosion and improve vegetation establishment on water repellent soils, suggesting that this can be a successful post-fire treatment (e.g. Osborn et al. 1967; Krammes and Osborn, 1969; Debano and Conrad, 1974). While wetting agents have not been used in wildland systems since the 1970's, they have are used extensively in agriculture and urban landscapes, which has lead to improvements in the effectiveness of these chemicals in diminishing soil water repellency (Kostka and Bially, 2005).

Recent work by Madsen et al. (Chapter 4 herein) provides evidence that the use of these recently-developed wetting agents significantly improves ecohydrologic properties required for plant growth within post-fire pinyon-juniper communities. They found that water repellent soil treated with a liquid wetting agent had significantly higher infiltration rates, soil water content, above and below ground biomass, plant density, and root depth than a water-repellent soil without wetting agents. The effect of wetting agents was explicit, seeds treated with wetting agents under a low water regime experienced aboveground biomass production that was 8 times higher than the control. The development of these wetting agents and their use in treating seeds of desirable species provides an innovative approach for alleviating the effects of soil water repellency on germination and establishment of native vegetation species, thus allowing them to better compete with invasive annual weed species such as cheatgrass.

The primary goals of this study are to first, compare survival and growth of the native plant species 'Anatone' bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve) to the invasive annual weed cheatgrass (*Bromus tectorum* L.), in presence of water repellent soil; and second, compare the effectiveness of wetting agents and soil tillage for ameliorating soil water repellency, and improving soil water content, seedling density, plant survival, and biomass.

MATERIALS AND METHODS

Study area

Effects of wetting agent application and simulated mechanical soil disturbance on post-fire WR soils were evaluated in a glasshouse experiment conducted from 10 February through 22 April, 2009 at Brigham Young University (BYU), Provo UT, USA. Soil used in the study was collected from the subcanopy of burned Utah juniper (*Juniperus osteosperma* (Torr.) Little) trees, within the boundaries of the 2007 Milford Flat wildfire. This fire was ignited by lightning on 6 July, 2007, and rapidly became Utah's largest wildfire on record, having burned over 145,000 ha upon its containment on 10 July, 2007. Soil was collected one year after the fire 13.7 km NW of Milford UT, USA (337415 E, 4255901 N, Zone 12) at the base of the Mineral Mountain Range. The soil is a coarse sandy loam, mixed, mesic Aridic Haploxerolls. Prior to the fire, the vegetation community at the study site was a Phase III, P-J woodland (i.e. "trees are the dominate vegetation and primary plant layer influencing ecological processes on the site" Miller et al., 2005), with Utah juniper and singleleaf piñon (*Pinus monophylla* Torr. & Frém.*)* as the predominant tree species. At the time of soil collection, the soil remained almost completely bare of live vegetation and exhibited water repellency. Previous studies showed (Chapter 4 herein) that the average water drop penetration time (WDPT) under the canopy of burned P-J trees was 87.6±4.28 minutes. The mean depth of the water repellent zone was (4.80±0.51 cm), with average minimum and maximum depths of 1.40±0.12 cm and 6.1±0.53 cm, respectively.

Study design

Soil was collected with minimal disturbance in large cylinders (30.5cm diameter by 36-cm deep) by pressing individual tubes into the soil with a front-end loader. Each tube was then modified for use as a growing pot by fastening permeable ground cloth around the bottom to secure the core within the tube. In the glasshouse, pots were designated to be planted with either bluebunch wheatgrass or cheatgrass. Soil treatments included: tilling, wetting agent application, both tilling and wetting agent application, and a control (no amelioration treatment). Arranged in a randomized block split-plot design, each treatment was replicated three times in five blocks for both species, totaling 120 sample units,.

Bluebunch wheatgrass seed was purchased from Granite Seed Company, Lehi, UT. Cheatgrass seed was collected near the area that soil cores were collected, within the boundaries of the Milford Flat fire, seven months prior to seeding. The total germination of each species was tested in 13 cm diameter petri-dishes using 3 replications of 100 seeds per species, and was found to be 65% germinable for bluebunch and 99% for cheatgrass.

The tilling treatment was designed to mimic the effects of an Ely-style anchor chain, a method commonly used in range management practices. In each tillage-treatment pot, the surface was tilled to mimic conditions created by an Ely chain using a hand-held spade. The spade was pushed into the soil to a depth of 10 cm and then rotated on a horizontal plane, with the vertex at the soil surface, until the bottom of the spade emerged from the soil. This motion was repeated four times in each growth pot assigned to receive a till treatment. Following the till treatment, 15 seeds of either bluebunch wheatgrass or cheatgrass were hand-pressed just under the soil surface in each pot.

The wetting agent "Soil Penetrant" (Aquatrols Corp., Paulsboro, NJ), which is composed of a blend of alkylpolyglycoside (APG) and ethylene oxide/propylene oxide (EO/PO) block copolymers was applied at 0.012 ml cm^{-2} after planting, when the pots were first watered. Throughout the course of the study pots were watered with a mist sprinkler system at a rate of 2.7 cm hr^{-1}. During the first watering each pot received 400 ml of water. To encourage seed germination, pots were watered over the next six days as needed in order to keep the soil moist. Following this period, pots were subsequently watered every 7 days for the duration of the study, with 400 ml delivered at each watering. Temperature of the glasshouse was set at 25ºC with a 12 h photoperiod.

Measurements

Several physical, and chemical hydrologic and vegetation response variables were chosen to assess treatment effects including: soil water content, soil and plant nitrate, plant density, above-ground biomass, and below-ground biomass. For each of the different water repellency amelioration treatments and the control, five pots were randomly selected for soil water content measurements. Soil water content was recorded continuously at the 1-3 cm soil depth, with EC-5 Soil Moisture Sensors in conjunction with Em5b data loggers (Decagon Devices, Pullman, WA).

Plant density was measured throughout the course of the study by recording the number of live seedlings every 3 days for all pots in the study. At harvest (61 days after seeding), roots were washed free of substrate, and below-ground and above-ground biomass (dried at 65 °C for 72 hrs) were measured separately.

Towards the end of the study, it was observed that cheatgrass plants growing within the wetting- agent treated soils appeared to show signs of nitrogen deficiency, with pale green to yellow leaves and a senescence of growth. To quantify these effects, soil and plant nitrate levels were analyzed by the Brigham Young University soil testing lab using chromotropic acid (CTA) (Haby 1989). Soil nitrate was measured from a sample taken from the top 15.2 cm of soil. Plant nitrate was obtained from a 0.5 g subsample of plant biomass taken after grinding and mixing all of the plants from a single pot.

Data analysis

Data were analyzed using SYSTAT 12 (Systat software inc. Chicago, IL), with significance determined at $P < 0.05$ level. Mixed model analysis was used to analyze soil water content, soil and plant nitrate, seedling density, percent survival of live germinable seeds, above-ground biomass, and below-ground biomass. Replications within each block were averaged; blocks were considered random. Plant density was also analyzed by normalizing the species densities by total germination percentage and combining species and treatment groups that did not differ significantly. For soil water content, repeated measure analysis was used. Seedling density was compared among treatments and soil water content was compared among treatments and watering periods. Treatments not found to be significant were combined for statistical analysis. For treatments found to affect the response variables, mean values of the response variables were separated using Tukey's Honestly-Significant-Difference (HSD) test.

RESULTS

Treatment, watering period, and treatment by watering period interactions were significant for soil water content ($F = 745.5$, $p < 0.001$; $F = 792.3$, $p < 0.001$; and $F = 89.0$, $p < 0.001$, respectively). Differences among treatments for soil water content were generally greatest at the beginning of the study and decreased over time (Fig. 1). Water content of soil treated with wetting agent was significantly higher than all other treatments for the first 5 watering periods. Beyond that point in time, soil treated with wetting agent differed only from the control. Water content in soils receiving the till + wetting agent treatment was higher than observed in soils receiving only the till treatment for the first three watering periods and was higher than the control for all watering periods except period eight. In general, tilling the soil did not significantly increase soil water content relative to the other treatments, however, over the course of the study, increases in soil water content appeared to be greater in tilled than in untilled soil.

At the end of the study, soil nitrate was similar for soils growing either bluebunch wheatgrass or cheatgrass ($F = 3.8$, $p = 0.061$), but differed significantly among the other treatments ($F = 63.0$, $P < 0.001$). As demonstrated in Fig. 2, soil and plant nitrate in pots receiving wetting agent and till + wetting agent treatments were similar to each other but were significantly lower than those in pots that did not receive a wetting agent treatment. Soil nitrate did not differ between control pots and pots receiving the till only treatment. Average soil nitrate concentration in pots receiving wetting agent and till + wetting agent treatments was 5.1 ±1.3 and 4.7±0.6 ppm, respectively; average soil nitrate concentration in pots treated with tilling and control pots averaged 36.9±3.6 and 53.4±5.0 ppm, respectively. Treatment and species main effects were significant for plant nitrate levels ($F = 12.6$, $p < 0.001$; and $F = 6.6$, $p = 0.016$, respectively). Species by treatment interactions were not statistically significant ($F = 0.2$, $p = 0.882$). No difference in plant nitrate levels was observed between bluebunch wheatgrass treatments. Nitrate in cheatgrass was lower in pots treated with wetting agent than observed in control pots or pots that received only the till treatment. No difference was observed between species for any treatment (Fig. 2).

Species, treatment, and species by treatment interactions for total density were significant ($F = 58.3$, $p < 0.001$; $F = 42.6$, $p < 0.001$; and $F = 3.7$, $p = 0.021$ respectively) (Fig. 3A). However, species was not a significant factor for density when species were normalized by the percentage of germinable seeds ($F = 4.0$, $p = 0.053$) (Fig. 3B). Densities in pots treated with wetting agent were similar regardless of tillage. After combining similar treatments (resultant treatment groups included: wetting agent, till, and control) treatment effects were significant for final density ($F = 34.6$, $p < 0.001$), and for peak seedling density ($F = 15.5$, $p = 0.001$). Peak densities were distinct for till, wetting agent, and control treatments (Fig. 3C). The till treatment produced the lowest peak densities; density in control pots averaged just less than both wetting agent treatments. Over the course of the study, seedling densities decreased by 55.2 % in control pots, 17.8 % in pots receiving the till treatment, and 11.9% in pots receiving either of the wetting agent treatment. At the end of the study, density in control pots and pots treated by tilling was different, although the difference was less pronounced compared to differences in peak densities; both of these values were lower than observed in pots receiving a wetting agent treatment (Fig. 3C).

Differences in above-ground biomass were attributable to species ($F = 24.7$, $p < 0.001$) and treatment main effects ($F = 12.1$, $p < 0.001$); species by treatment interactions were not significant ($F = 0.3$, $p = 0.856$). Pair-wise comparisons of the different treatments and the control, by species, are shown in Fig. 4. Till, wetting agent, and till + wetting agent treatments yielded similar above-ground biomass values for both species. Although above-ground cheatgrass biomass was consistently higher in treated pots than in control pots, differences were only significant between the till + wetting agent treatment and the control. In contrast bluebunch wheatgrass above-ground biomass was greater in treated than untreated soil.

Differences in below-ground biomass were attributable to both species ($F = 34.9$, $p < 0.001$) and treatment ($F = 16.8$, $p < 0.001$) main effects; species by treatment interactions were not significant ($F = 0.6$, $p = 0.619$). Cheatgrass below-ground biomass was greater in pots receiving either of the wetting agent treatments than the control pots. Pots receiving the till treatment exhibited below-ground biomass intermediate to the control and wetting agent treatments, but did not differ significantly from those treatments. Bluebunch wheatgrass below-ground biomass showed a similar response between the wetting agent treatments and the control, however, for this species the till treatment resulted in lower below-ground biomass production than wetting agent treatments.

On a per-plant basis, treatment main effects were found to be significant for above-ground biomass ($F = 3.5$, $p = 0.018$), but no other main effects or interactions were significant for either above (Species: $F = 0.1$, $p = 0.754$; Species × Treatment: $F = 0.3$, $p = 0.813$) or below-ground biomass (Species: $F = 0.2$, $p = 0.686$; Treatment: $F = 0.2$, $p = 0.870$; Species × Treatment: $F = 2.3$, $p = 0.078$), and no difference in either above or below ground biomass was observed from any of the species-treatment combination comparisons (Fig. 4). Differences in above-ground to below-ground biomass ratio attributable to treatment main effects were observed to be significant ($F = 3.4$, $p = 0.029$), but neither species main effects nor species by treatment interactions were significant ($F = 2.5$, $p = 0.122$, and $F = 0.2$, and $p = 0.888$ respectively).

DISCUSSION AND CONCLUSIONS

The results of this study support earlier observations that wetting agents can ameliorate post-fire water repellency and subsequently help restore ecohydrologic function, in conjunction with reseeding efforts (e.g. Osborn et al., 1967; DeBano et al., 1967; DeBano and Rice, 1973; DeBano, 1981). Increases in seedling germination and survival, and corresponding increases in biomass associated with wetting agent application may be specifically related to increases in soil water content during periods when germination and early growth occurred. In this study, the difference in soil water content between the wetting agent treatments and the control was most pronounced at the beginning of the study and decreased over time. The observation that differences in soil water content between pots treated with wetting agent and control pots became less pronounced over time could be explained at least in part by the relatively and progressively higher plant density and biomass, and correspondingly higher water use, in pots treated with wetting agent compared to control pots.

When normalized for germinability, cheatgrass and bluebunch wheatgrass responded similarly to wetting agent treatments. These results may suggest that soil water repellency affects both species similarly. However, further research is merited within a field setting. As stated above, water repellency most likely impairs plant survival by decreasing available soil water content. Cheatgrass, can germinate either in the fall, winter, or early spring depending on weather conditions (Roundy et al., 2007); perennial grass species such as bluebunch wheatgrass require a longer germination period and growing season to become established (Roundy et al., 2007). As a result, cheatgrass may be favored in areas with water repellent soils because it could potentially complete its life cycle, or at least develop a sufficient root system at times when moisture is available in the upper, wettable soil surface layer. Regardless of whether cheatgrass is able to invade before native plant species become established in the presence of water repellent soil, the urgency of establishing desired species is critical in order to prevent a transition to a weed dominated ecosystem (Young and Evans, 1978). For these reasons post-fire treatments which neglect the effect of soil water repellency on revegetation success may fall short, with the system remaining in a degraded state.

Towards the end of the study it was observed that cheatgrass plants growing in soil treated with wetting agent appeared to show signs of nitrogen deficiency, including pale green to yellow leaves and a senescence of growth. Analysis of nitrogen concentration at the end of the study showed that soil nitrate levels were significantly reduced in pots treated with wetting agent. Thus, beyond alterations in soil water dynamics, application of a wetting agent may further influence soil conditions by changing nutrient availability. These results may suggest that soil water repellency may reduce leaching of soil nutrients within the soil profile. Enhanced infiltration and percolation associated with treating water repellent soil with wetting agent may allow for leaching of nutrients from the top layers of the soil profile, whereas previously water repellency prevented the downward leaching of the water and nutrients.

Nutrient availability, including nitrate level has been observed to influence vegetation composition (Blank et al., 2007) and susceptibility to invasive plant species (Monaco et al., 2003). Some have suggested that increases in available soil nitrogen following wildfire (Covington et al., 1991) may benefit cheatgrass more than many native perennial species (Monaco et al., 2003; Blank et al., 2007). When nitrogen resources are high, invasive annuals, such as cheatgrass, tend to dominate (Vasquez et al., 2008; Bidwell et al., 2006; Blumenthal, 2006). Similarly, reductions in nitrate availability have been suggested as potential methods to increase the relative ability of native plant species to compete with introduced annual species, at least temporarily (Monaco et al., 2004; Vasquez et al., 2008; Mazzola et al., 2008). As suggested by these other studies, the observed reduction in soil nitrate associated with wetting agent application in this study appeared to affect cheatgrass more than it did bluebunch wheatgrass. Nitrate concentration in cheatgrass biomass from soil treated with wetting agent was lower than that from untreated soil. In contrast, there was no difference in nitrate concentration in bluebunch wheatgrass biomass was observed between the control and wetting agent treatments. Therefore, application of wetting agents may have some benefit for reseeding native bunchgrass species in sites susceptible to cheatgrass invasion. Potentially, sites that have been treated with wetting agent, and have had sufficient time for precipitation events to allow for nitrate leaching, would show a decrease in cheatgrass survival. Unlike treatments involving additions of carbon, which have short-term effects on nitrogen availability through immobilization from soil microbes (i.e. Mazzola et al., 2008), application of wetting agents may have more long term effects, through leaching nutrients from the soil profile. Others have also observed different responses to wetting agent application from different plant species (DeBano and Conrad, 1974). Further research is merited to determine the long-term effects of wetting agent application on vegetation community composition and the proximate mechanisms producing those effects.

Soil tillage designed to simulate anchor chaining showed mixed results. Tillage treatments had lower seedling emergence than both the control and wetting agent treatments, but significantly less seedlings desiccated over the period of study. At the end of the study, the till treatment had higher seedling densities in relationship to the control. Potential reasons for the till treatment having the lowest peak seedling densities may be due the tilling treatment decreasing soil moisture availability to the seeds. When the tilling treatment was implemented water repellent soil was brought to the soil surface. In this treatment we would suspect at the seed scale, soil moisture would have been quite low for those seeds in contact with the water repellent soil, and subsequently had poor germination. However, within this same treatment, there may have also been seeds that were associated with breaks in the water repellent zone that would create conditions favorable for germination. These breaks may have also increased seedling survival by creating a zone where the seedlings could be connected with the underlying soil moisture reserves, and subsequently may be the reason that very few of the seedlings desiccated in this treatment.

Overall these results validate wetting agents and mechanical soil disturbance as effective means for mitigating the effects of soil water repellency and promoting the establishment of seeded species. Wetting agent application appears to be superior for improving seedling survival and biomass production in comparison to tilling the soil. Furthermore, no additional benefit is realized by combining wetting agent and till treatments. A limitation to this study is that glasshouse conditions do not exactly replicate field conditions. Future research is merited for repeating these studies in field conditions, to evaluate the long-term effects of wetting agent application and anchor chaining on final plant cover over desired and invasive species.

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FIGURES

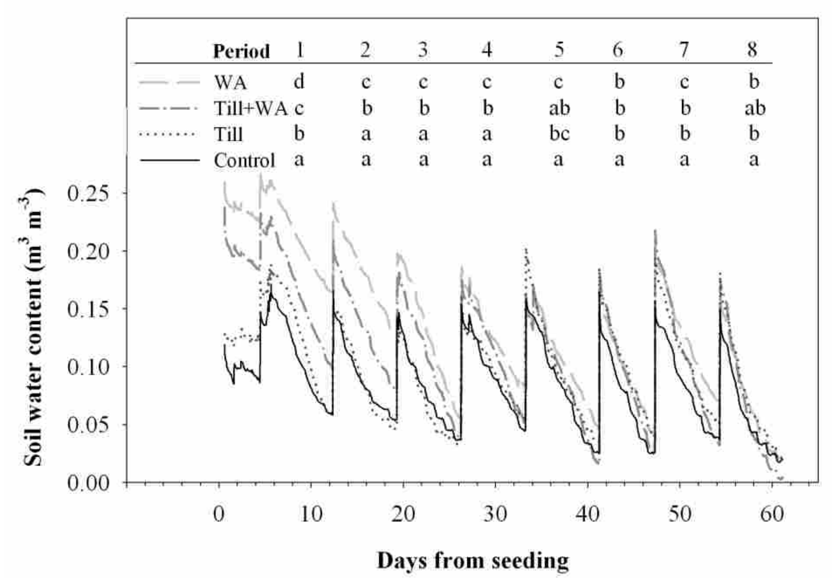

Fig. 1. Soil water content over the course of the study, with significance denoted by watering periods for comparing control, till, wetting agent (WA), and T + WA treatments.

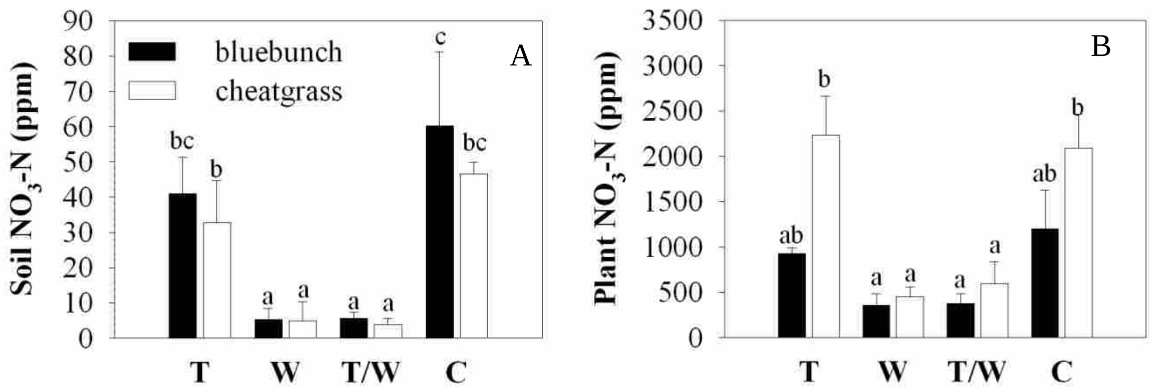

Fig. 2. Soil (A) and plant (B) nitrate levels at the end of the study comparing the treatments control (C), till (T), wetting agent (WA), and T + WA.

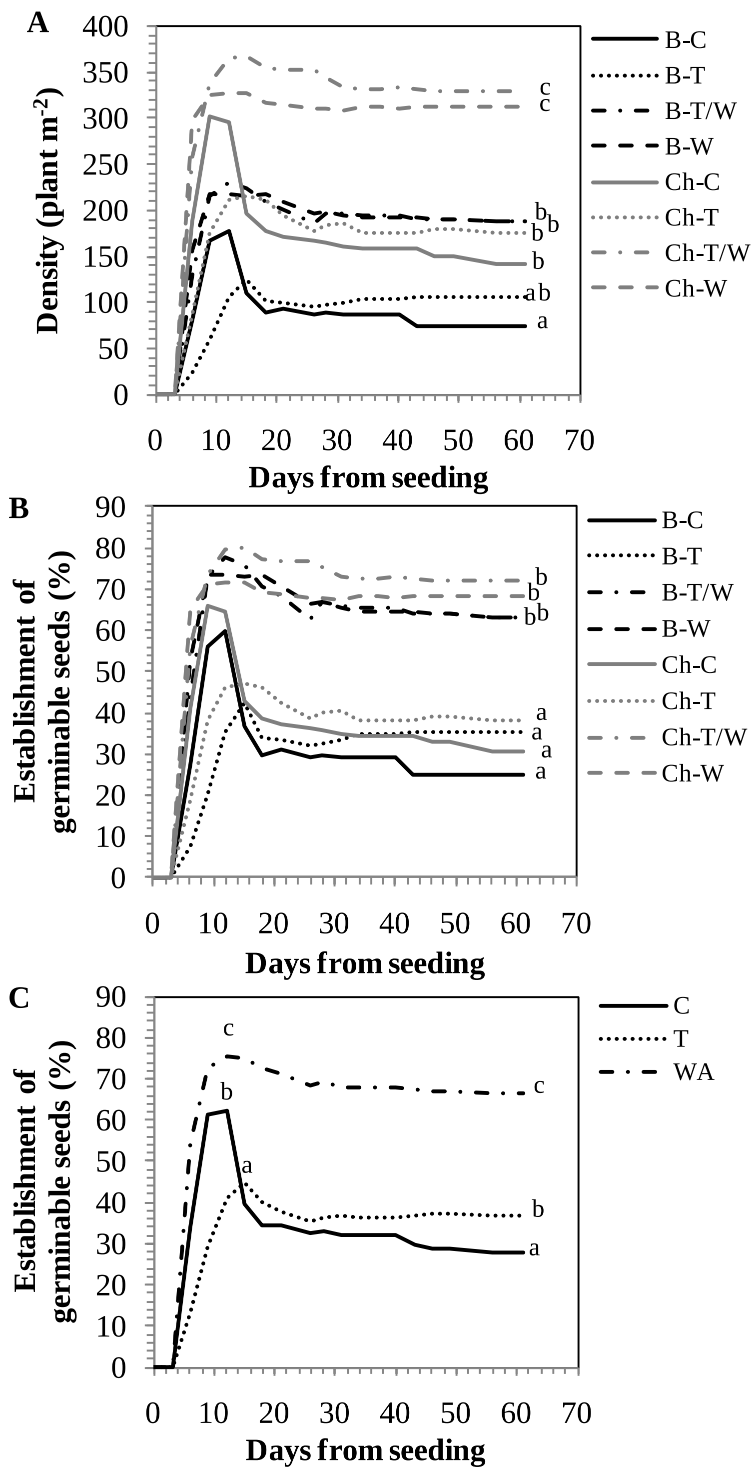

Fig. 3A. Seedling density of cheatgrass (Ch) and bluebunch (B) for the treatments control (C), till (T), wetting agent (WA), and T + WA. **B.** Density normalized by germinability. **C.** Species and WA and T + WA combined.

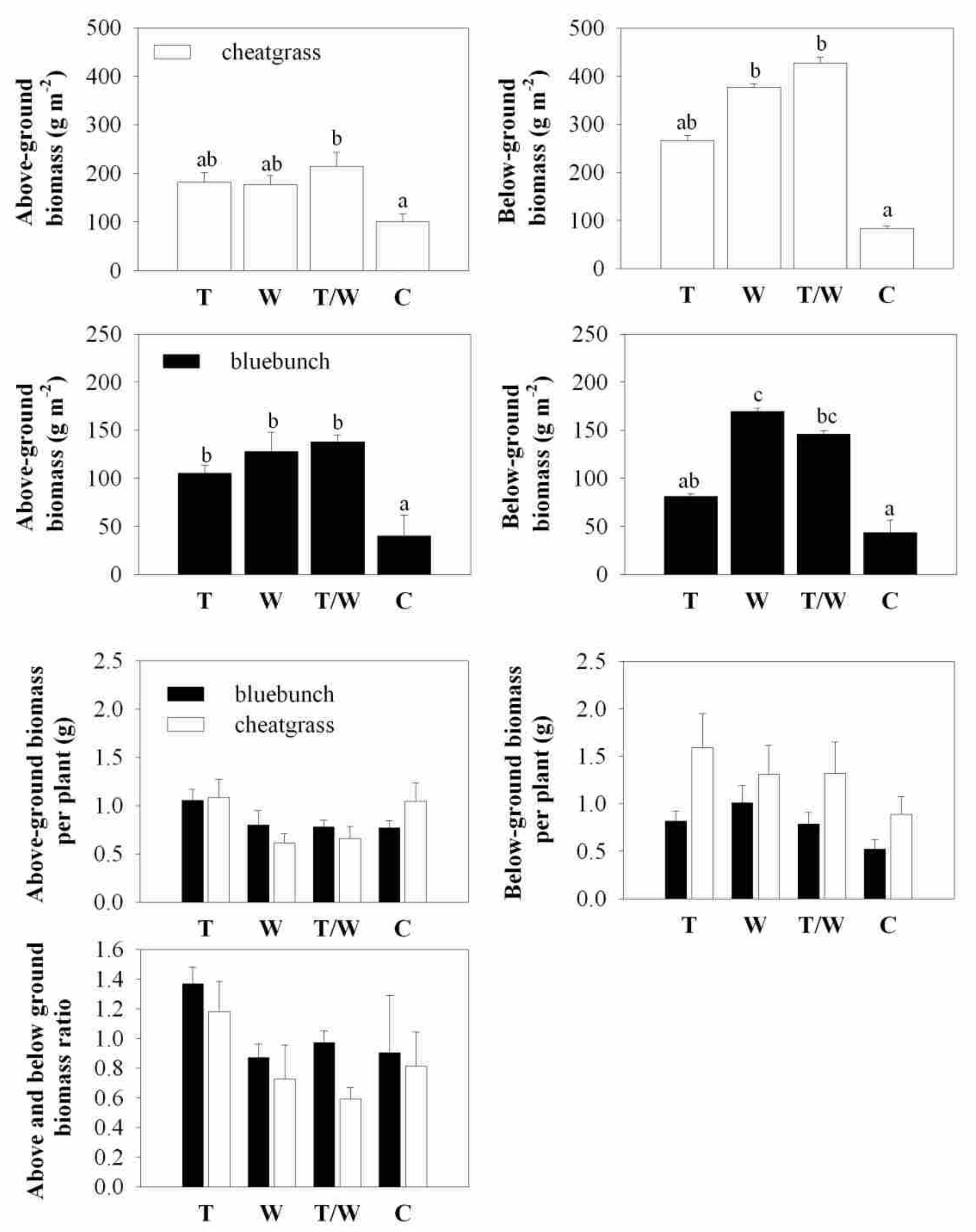

Fig. 4. Above and below ground biomass of cheatgrass, and bluebunch wheatgrass grown on water repellent soil, for control (C), till (T), wetting agent (WA), and T + WA treatments. Significant differences ($P < 0.05$) are shown by unique letters.

Chapter 6: Conclusions and Future Research

Results of this dissertation extend opportunities for enhanced post-fire rangeland monitoring and restoration through: evaluating and further developing feature extraction techniques for quantifying piñon-juniper (*Pinus-Juniperus*) P-J tree canopy cover and density from high resolution aerial photographs; combining feature extracted data with spatial field measurements of soil water repellency for assessing post-fire impacts at the landscape scale; improving our understanding of the ecohydrologic significance of soil water repellency as a temporary ecological threshold that impairs native plant materials establishment; and evaluation of wetting agent technology to ameliorate post-fire soil water repellency and improve reseeding success.

Feature extraction techniques used in this study provide an accurate, cost-effective procedure for assessing important rangeland indicators, including: density, cover, and extent of P-J tree encroachment. High correlations found between field plot data and remotely sensed imagery provides evidence to support extrapolation of cover data between the two approaches when assessing rangeland status. Estimates of tree density were limited by image resolution (0.25 cm pixel size was used in this study); however, coupling field-based measurements with feature extraction techniques magnifies both measurement types, allowing feature extraction data to be calibrated with actual tree counts, and allowing for monitoring to take place at the landscape rather than the plot level.

To the best of our knowledge this study is unique in that it is the first to quantify the spatial distribution and ecohydrologic effects of soil water repellency in a burned P-J woodland. Results indicate that post-fire patterns of soil water repellency were highly correlated with pre-fire P-J woodland canopy structure, soil water content, infiltration, and revegetation success. One year after the fire, soil water repellency was found to extend just beyond the canopy edge, while subcritical water repellency extended a full canopy radius beyond the canopy edge. Water repellency in this zone was still strong two years after the fire. The severity of water repellency was inversely related to unsaturated hydraulic conductivity, soil water content, and revegetation recovery. Reduction of these ecohydrologic variables was most pronounced in the critical water repellency zone, but a decrease in values was also found where subcritical water repellency was present, albeit to a lesser extent.

Based on the strong relation between soil water repellency and pre-burn canopy cover, analysis of remotely-sensed imagery appears to be an effective method for scaling up the spatial distribution of water repellent soils to the fire boundary scale and allowing a more accurate assessment of the extent of water repellency and its severity. While the GIS modeling concept proposed in this study for mapping soil water repellency has merit, the approaches proposed require further refinement and testing.

Research using wetting agent technology within glasshouse studies suggested that within burned P-J woodlands, soil water repellency can promote runoff and disconnect seeds/seedlings from the underlying soil moisture reserves, thereby leaving the seed/seedling without adequate soil moisture. It is speculated that field conditions would likely have resulted in an even greater difference is seedling survival. Potentially the cycle of seedling emergence and desiccation may be frequent in the field, resulting in a loss of residual or aerially-seeded seeds from the seed bank. Thus, results of this study indicate that soil water repellency is acting as a temporary ecological threshold; impairing establishment of desired species within the first few years after fire, and thereby leaving resources available for weed invasion after soil water repellence has diminished.

These results also provide evidence that wetting-agents can ameliorate post-fire water repellency and subsequently help restore ecohydrologic function in conjunction with reseeding efforts. In these research studies the effect of wetting agents was explicit. Wetting-agents significantly increased soil moisture availability, which was correlated with seedling emergence and survival, and above and below ground biomass. Biomass was several hundred percent greater in treated soils than soils not treated with wetting agent.

This research, provides evidence that wetting agent technology should be further field-tested in wildland systems impaired by post-fire soil water repellency. If proven successful wetting agents could reduce seeding costs by reducing frequent seeding failures in semiarid rangelands, and by increasing plant establishment, thereby enabling lower seeding rates.

APPENDIX

INVENTION DISCLOSURE

Innovative Use of Seed Coating Technologies for Applying Wetting Agents to Water Repellent Soil

Inventor: Matthew D. Madsen

Abstract

The present invention provides an innovative method for improving seedling establishment on post-fire water repellent soils. This method utilizes standard seed coating technologies in a novel way, to enable the coating of seeds with wetting agents. Releasing wetting agents directly around a seed exposed to hydrophobic soil will preferentially increase the soil water availability and duration, for that seed, through the creation of a hydrophilic conduit. This conduit will allow precipitation to drain from the surrounding hydrophobic soil towards the seed, and will enable soil moisture to move upwards by capillarity towards the seedling as the soil surface dries. Increased seedling establishment through this technology would 1) decrease the potential for weed invasion, and 2) improve soil stability by increasing soil infiltration directly, as described; and indirectly, through increases in above and below ground biomass.

Section I. Problem statement

Fire suppression of wildland ecosystems has produced large decadent stands of older growth, even-aged forest and brush stands, which upon burning result in high intensity large scale catastrophic wildfires. Fires of this nature impair watershed stability and water quality through vegetation denudation, and generate concern for the expanding urban-wildland interface, where accelerated runoff and soil erosion have the potential to damage down slope residential communities. The invasion of weedy species is also a major concern. Following fire these systems often remain weed dominated for several years, causing significant impacts to ecological services. Consequently, it is imperative that we develop post-fire conservation approaches that maintain soil stability and enhance the revegetation success of desired species in order to preserve the ecological integrity of our wildlands and adjacent urban interfaces.

After a fire, the ability of ecosystem to recover is dependent on the extent to which ecological processes have been altered. Modification of the soil through the development of a hydrophobic (or water repellent) layer is one alteration which can significantly limit site recovery. Wildland vegetation can create a hydrophobic layer in the first few centimeters of the soil profile. During a fire, heat can volatilize organic substances within the litter and upper hydrophobic soil layers. These volatilized compounds then move downward into the soil, condensing within the cool underlying soil layers. This results in a wettable layer at the soil surface and an intensified hydrophobic zone a few centimeters below the soil surface. The development or enhancement of this hydrophobic layer has severe implications for revegetation success, runoff, and soil erosion. Seeds which germinate within the soils upper wettable layer typically desiccate, as a result of the water repellent layer disconnecting the seedling from the underlying soil moisture reserves (Fig. 2A and 3A). The lack of seedling establishment allows for continued soil erosion and provides the opportunity for invasion of annual weeds in subsequent years, when sown seeds are no longer viable.

The arrangement of a wettable soil layer overlying a water repellent layer also has severe implications for water runoff and soil stability. During a rainfall event the upper wettable layer is quickly saturated due to the underlying water repellent layer impeding infiltration (Fig 3A). On steep slopes, when this wettable layer becomes saturated from high intensity rainfall events water, soil, and debris can quickly flow down slope, which causes site degradation and property damage if it is within the wildland urban interface.

Large amounts of public funds are spent each year on post-fire rehabilitation treatments. The most effective post-fire rehabilitation treatments are those that immediately provide surface cover. However, these methods are costly, for example straw mulching has been shown to range in-between \$1000–3000 ha^{-1}, while hydromulching can range between \$2350-\$4700 ha^{-1}. Consequently, applying such strategies can be almost impractical at large scales. There is currently a need for effective post-fire rehabilitation treatments which can be applied at the landscape scale that ameliorate the influence of hydrophobic soil and establish desirable plants back into the system.

Section II. Prior technology

Use of commercially available wetting agents may provide an alternative post-fire restoration approach where hydrophobicity and limited soil moisture availability are preventing site recovery. Wetting agent molecules are hydrophobic on one end and hydrophilic on the other. Upon entering the soil the hydrophobic end of the wetting agent chemically attaches to the non-polar water repellent coating on the soil particle; while the hydrophilic end of the agent is able to attract water molecules allowing soil moisture to be absorbed in the upper hydrophobic soil layers.

Various small plot post-fire research projects in the late 1960’s and 1970’s located in the chaparral mountains of southern California have shown that the application of wetting agents after a fire can reduce soil erosion and improve vegetation establishment. These studies suggest that the application of wetting agents can be a successful post-fire treatment. While wetting agents have not been used in wildland systems since the 1970’s, they have been extensively used and further developed in various aspects of the agricultural industry, with particular use in turf production. Subsequently, the effectiveness of these chemicals in diminishing soil hydrophobicity has been improved. The development of these wetting agent products provides an innovative approach for alleviating the effects of hydrophobicity on runoff and soil erosion, and revegetation success.

While these results are promising, application of soil amendments is typically not practical for the revegetation of wildland systems, due to the large areas and low economic value of the land to be treated. Commercially available wetting agent products are particularly costly. Furthermore, the application of these chemicals to a wildland landscape is difficult at best.

Section III. Invention

Our invention provides an economical and innovative solution for applying wetting agents across large areas, through the use of seed coating technology. For the reclamation of post-fire hydrophobic soils, wetting agents can be coated around the seed, allowing the wetting agent and the seed to be dispersed together by an aircraft, drill or other seeding methods. The release of the wetting agent preferentially increases soil water content and duration of soil water availability for seeds and seedlings by creating a hydrophilic patch around the seed in a hydrophobic field (Fig. 2). This allows precipitation to drain from the surrounding hydrophobic soil towards the seed, as well as for soil moisture to move upwards by capillarity towards the seedling as the soil surface dries (Fig. 2). Through the development of this microsite, plants can grow their roots through the hydrophobic layer connecting the plant with the underlying soil moisture reserves, while increasing soil stability and improved watershed function (Fig. 2).

There are several soil wetting agent products on the market. Our research has shown that a concentrated form of the recently developed wetting agent “Soil Penetrant” (Aquatrols, Paulsboro, NJ) is affective in ameliorating soil water repellency; however, there may be other products which have similar results. In concentrated form the chemistry of the wetting agent (non-ionic surfactant, which is a blend of alkylpolyglycoside (APG) and ethylene oxide/propylene oxide (EO/PO) block copolymers) remains in a highly viscous state. To coat the wetting agent around the seed the wetting agent needs to first be attached to a carrier. We have evaluated several carriers based on their absorption capacity of wetting agent (in order to minimize the amount of carrier which needs to be coated around the seed) and ability to release the wetting agent into the soil with rainfall. Based off of our laboratory research we have chosen to use -325 RVM as a carrier, which is a dried montmorillonite clay (Oil-Dri Corporation of America, Alpharetta, Georgia) However, other carriers may also be effective such as potato starch, molecular sieve, diatomaceous earth, gum Arabic, lime, and bentonite.

Seed coating technology has evolved to allow for multiple seed coating amendments to be layered around the seed. For the application of wetting agents it would be advantageous to first apply a “plant protectant” layer around the seed to physically separate the seed surface from the wetting agent. Super hydrating polymers would fit this role while providing an additional soil amendment, to increase seedling establishment. Super-hydrating polymers have been shown to improve seedling growth and establishment by increasing the amount and duration of plant available soil water. Coating of these products around the seed can be performed through standard commercial seed coating equipment, using binders or adhesive. Binders may also be incorporated near the end of the coating process to harden the outer layer.

Section IV. Application

The proposed technology could be applied to several different species of plant materials where soil moisture limits establishment after wildfire. Treating of rangelands with coated seed would reduce costs by producing higher rates of plant establishment, thereby enabling the use of fewer seeds in the treatment. Furthermore, this technology may help reduce weed invasion by giving desired species a hydrologic advantage over weed species. Applying wetting agent coated seeds after a fire may also help decrease runoff and erosion by: 1) directly improving the soil’s infiltration capacity, 2) protecting the soil surface from raindrop impact with increased vegetation growth, and 3) anchoring surface soil layers as roots penetrate below the water repellent layer (Fig. 3). Additionally, the larger seed size will improve aerial reseeding efforts by increasing uniformity in seeding rates and species composition. Finally, coating seeds with wetting agents may prevent seed loss by: 1) deterring insect and herbivore predation due to unpalatability of the seed coating amendments, 2) preventing the seed from being carried off site by wind and water, due to the considerable increase in seed weight from the coating, and 3) helping the seed adhere to the soil and eroding soil grains, thus preventing seed loss from wind and water erosion.

In conclusion, the effects of large, high-severity wildfires will continue to be a problem, therefore, cost effective post-fire rehabilitation treatments are imperative. This technology has the potential to meet this exigency and consequently sustain wildland ecological services.

FIGURES

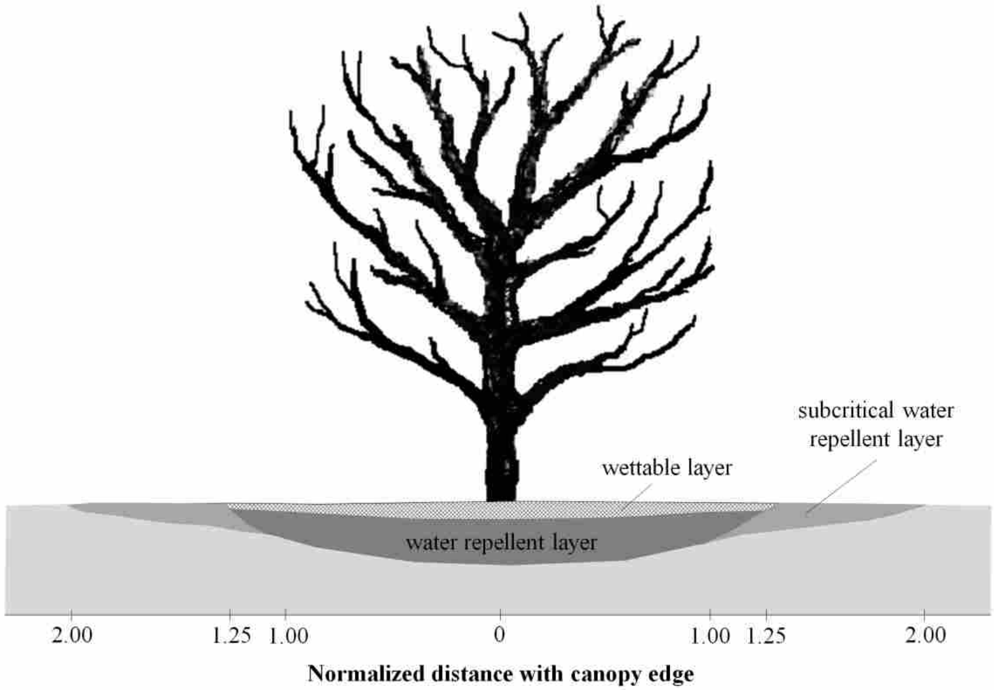

Fig. 1. Schematic diagram of a burned juniper tree canopy, showing areas of water repellent soil and subcritical water repellent soil.

Fig. 2. **A.** Schematic diagram of a seed coated with super-hydrating polymers and a wetting agent. **B.** Precipitation releases wetting agents into the soil which creates a hydrophilic conduit to connect underling soil moisture with the upper wettable layers. **C.** Polymers retain water from previous precipitation events for seed germination and seedling growth.

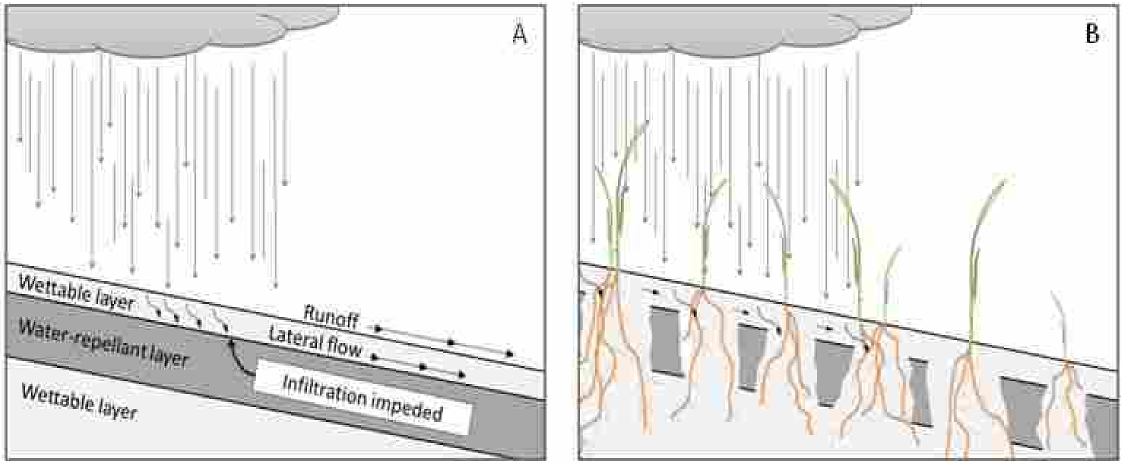

Fig. 3. **A.** Soil WR impedes infiltration, causing the saturation of the upper wettable soil layer, and reduces surface runoff and soil erosion (Modified from DeBano, 1969). **B.** With our innovative seed coating technology soil WR is potentially overcome around the seedling, allowing roots to penetrate through the soil profile, promoting soil stability.

CONTACT INFORMATION

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CAREER OBJECTIVE

Restoration Ecologist
Research scientist, with emphasis in post-fire restoration methods and materials, seed coating technology, ecohydrology, geographic information systems (GIS), remote sensing, wildland soils, and plant ecology

EDUCATION

Doctorate of Philosophy,
Institution: Brigham Young University, Provo, UT
Field of study: Wildlife and Wildlands Conservation, GPA 3.8
Years attended: Aug. 2006-Estimated Graduation Dec. 2009
Advisor: Steven L. Petersen

- Dissertation Topic: "Influence of Water Repellency on Post-fire Revegetation Success and Management Techniques to Improve Establishment of Desired Species"

Master of Science
Institution: Utah State University, Logan, UT
Field of study: Soil Science, GPA 3.6
Years attended: Jan. 2005-Aug. 2006
Advisor: David G. Chandler

- Thesis Topic: "Measurement of Fine Spatial scale Ecohydrologic Gradients in a Pinyon-Juniper Ecosystem"

Bachelor of Science,
Institution: Utah State University, Logan, UT
Field of study: Watershed and Earth Systems
Years attended: Jan. 2003-Dec. 2004

Associate of Science
Institution: Snow College, Ephraim, UT
Field of study: Watershed and Earth Systems
Years attended: Sept. 1999-Dec. 2002

EXPERIENCE

Research and Teaching Assistant Brigham Young University
Dept. of Plant and Wildlife Science, Provo, UT
(Aug. 2006-Present)
Research Assistant

- Investigation and modeling of rangeland ecological sites susceptible to fire induced soil water repellency and its effects on soil stability and revegetation success of desired species
- Determine the suitability of recently developed wetting agents, and super hydrating polymers for use in wildfire rehabilitation to improve germination and subsequent competitive availability of native plant species against annual weed invasion

Teaching Assistant

- In conjunction with a graduate level landscape ecology course developed and taught remote sensing and GIS laboratories.
- For an undergraduate course in natural resource planning helped develop and teach GPS, GIS and natural resource management fundamentals
- For an undergraduate course in wildlife management, worked with students to understand and perform habitat assessments, and several wildlife capture and immobilization techniques
- For an undergraduate course in soil science, helped teach introductory soil principles on the nature and properties of soils

Research Assistant Utah State University
Dept. of Plants, Soils and Climate, Logan, UT
(Jan. 2005-Aug. 2006)

- Ecohydrological measurements of soil surface properties related to infiltration in a pinyon-juniper woodland
- Field testing of produced water for desert soil stabilization
- Developed hydrologic field testing equipment for application in a rangeland setting

Hydrology Technician USDA Forest Service, Tongass National Forest, Sitka, AK
(May 2004-Aug. 2004)

- Determined stream channel classifications, applied forest wide standards in relation to timber harvest and stream protection
- Prepared digital cartographic data and operated GIS software for data documentation for input maps and map inventories

Hydrology Technician, Cirrus Ecological Solutions, Logan, UT
(Feb. 2003-April 2004)

- Water quality and quantity sampling in numerous streams and springs in association with underground coal mining activities in order to determine the potential impact of long-wall coal mining on two coal tracks on the Manti-LaSal National Forest.
- Perform TMDL water quality studies for the Bear River watershed

Excavator and Rancher, Madsen Construction/Livestock, Mayfield, UT
(1990-2006)

- Operated heavy equipment in construction of various agricultural water development projects
- Worked on range improvement projects; which included vegetation removal, re-seeding, development of springs and stock watering ponds
- Helped raise various agricultural crops in conjunction with a large sheep and elk ranching operation

RESEARCH FUNDING

Funded Grants

Primary author on grants obtained for funding of my PhD research. Due to my status as a graduate student, grants were submitted with Steven L. Petersen (my major professor) or Bruce Roundy as first author.

Roundy, B.A. M.D. Madsen, S.L. Petersen, and V.J Anderson. 2009. Innovative Use of Seed Coating Technologies for Restoration of Infiltration and Functional Plant Communities in Burned Semi-Arid Rangelands. USDA Rangeland Research Program ($436,600).

Madsen M.D. 2009. Brigham Young University Graduate Studies Fellowship Award ($6,000).

Petersen, S.P., M.D. Madsen, and B.A. Roundy (co-principal investigators) and A.G. Taylor, S. Barclay, and D.G. Chandler (collaborators). 2008. Innovative Use of Seed Pelleting Technologies for the Restoration of Arid and Semi-Arid Rangelands. State of Utah, Invasive Species Mitigation Fund ($66,022).

Petersen, S.L., M.D. Madsen, B.A. Roundy, B.G. Hopkins and R.F. Miller. 2008. Management Techniques to Improve Establishment of Desired Species in the Presence of Hydrophobic Soil. Natural Resources Conservation Service, Conservation Innovation Grants. ($56,929).

Madsen M.D. 2008. Charles Redd Grant ($1,200).

Petersen S.L., and M.D. Madsen. 2007. Brigham Young University MEG grant ($20,000).

RESEARCH

Published Manuscripts

Madsen, M.D., D.G. Chandler, and J. Belnap. 2008. Spatial Gradients in Ecohydrologic Properties within a Pinyon-Juniper Ecosystem. Journal of Ecohydrology. DOI: 10.1002/eco.29

Madsen, M.D., and D.G. Chandler. 2007. Automation and use of Mini Disk Infiltrometers. Soil Sci. Soc. Am. J., 71:1469-1472.

Madsen, M.D., D.G. Chandler, and W.D. Reynolds. 2007 Influence of experimental bias and boundary conditions on saturated core hydraulic conductivity Soil Sci. Soc. Am. J., 72:750-757.

Lebron, I., M.D. Madsen, D.G. Chandler, D.A. Robinson, O. Wendroth, and J. Belnap. 2007. Ecohydrological controls on soil moisture and hydraulic conductivity within a pinyon-juniper woodland. Water Resour. Res., 43, W08422, doi:10.1029/2006WR005398.

Madsen, M.D. 2008. Measurement of Fine Spatial scale Ecohydrologic Gradients in a Pinyon-Juniper Ecosystem. Thesis. Utah State University, Logan Utah.

ABSTRACTS

Madsen, M.D., and S.L. Petersen. 2009. Influence of Post-fire Soil Water Repellence and Simulated Rainfall Regimes on Revegetation Success. AGU Chapman Conference Examining Ecohydrological Feedbacks of Landscape Change Along Elevation Gradients in Semiarid Regions. Boise and Sun Valley, ID. October 4-8. Poster Session.

Chandler, D.G., M.S. Seyfried, and M.D. Madsen. 2009. Infiltrability Response to Vegetation and Fire Across a Sage-Steppe Catchment. AGU Chapman Conference Examining Ecohydrological Feedbacks of Landscape Change Along Elevation Gradients in Semiarid Regions. Boise and Sun Valley, ID. October 4-8. Poster Session.

Madsen, M.D., S.L. Petersen, and D.G. Chandler. 2009. Postfire water repellency: extent, severity, and restoration within a pinyon-juniper ecosystem. United States Regional Association of the International Association for Landscape Ecology. April 12-16, 2009 Snowbird, UT. Poster Session.

Madsen, M.D., B.D. Davis, S.L. Petersen, and D.L. Zvirzdin. 2009. Comparison of pinyon and juniper cover and density measurements obtained through remotely sensed imagery and field based rangeland studies. Annual Meeting for the Society of Range Management. Feb. 8-12, 2009. Albuquerque, NM. Poster Session.

Madsen, M.D., S.L. Petersen, B.A. Roundy, A.G. Taylor and B.G. Hopkins. 2009. Innovative Use of Seed Coating Technologies for the Restoration of Soil Wettability and Perennial Grasses on Burned Semi-Arid Rangelands. Annual Meeting for the Society of Range Management Feb. 8-12, 2009. Albuquerque, NM. Oral Presentation.

Madsen, M.D., S.L. Petersen, and B.A. Roundy. 2009. Postfire hydrophobicity: spatial extent, severity, and restoration. Utah State Annual Meeting for the Society of Range Management. November 6-7, 2008. Provo, UT. Oral Presentation.

Madsen, M.D. and S.L. Petersen. 2008. Influence of Postfire Water Repellency: Assessment of the Milford Flat Fire. [abstract]. Annual Meeting for the Society of Range Management. January 26-31, 2008, Louisville, KY.

Chandler, D.G. and M.D. Madsen. 2008. Spatial Gradients In Ecohydrologic Properties within a Pinyon-Juniper Ecosystem. American Geophysical Union, Fall Meeting, Abstract # H31E-0919.

Madsen, M.D., and D.G. Chandler. 2007. Automation and Use of Mini Disk Infiltrometers. Inland Northwest Research Alliance. Environmental Sensing Symposium, Boise State University. Poster Presentation.

Madsen, M.D. and B.A. Roundy. 2006. Brigham Young University: Current Research in the Great Basin. Workshop on Collaborative Watershed Management & Research in the Great Basin Reno, NV. Poster Session.

Madsen, M.D., and D.G. Chandler. 2006. Spatial and Seasonal Dependence of Vegetation Related Soil Hydrologic Properties in a Pinyon-Juniper Woodland. USU, Water Initiative, Spring Runoff Conference. Oral Presentation.

Wendroth, O., I. Lebron, M.D. Madsen, D. Robinson, J. Belnap, and D.G. Chandler. 2006. Spatial Process of Soil Hydrological State Variables in Pinyon-Juniper Woodland. Soil Science Society of America Conference, 70th Annual Meeting of the Soil Science Society of America, Indianapolis, IN. Poster Session.

Chandler D.G. and M.D. Madsen. 2005. Small Scale Variability of Infiltration and Hydraulic Conductivity in a Pinyon-Juniper Ecosystem. Soil Science Society of America Conference 69th Annual Meeting of the Soil Science Society of America, Salt Lake City, UT.

Lebron, I., D.G. Chandler, D.A. Robinson, J. Belnap and M.D. Madsen. The effect of anthropogenic disturbance in the ecohydrology of Pinyon Juniper woodlands with soil biocrust. American Geophysical Union Fall Meeting, San Francisco, CA. Dec 5-9, 2005.

RECOGNITIONS

- Second place Ph.D. student poster presentation contest. Society for Range Management annual meeting. Albuquerque, NM. Feb. 8-12, 2009.

- Featured in Overwatch Geospatial News for developing an effective and efficient method for quantifying juniper tree canopy cover and density, directly from high resolution photographs. Jan/Feb 2009 news letter. (http://www.featureanalyst.com/newsletters/JanFebnews.htm).

- Brigham Young University Graduate Studies Fellowship Award ($6,000).

- Third place graduate student oral presentation competition. Brigham Young University. Provo, UT. Dec. 2008.

- Featured in the Daily Herald newspaper as a wildfire grant recipient. Saturday, Aug. 9, 2008. (http://www.heraldextra.com/content/view/276113/)

COMPUTER SKILLS

GIS/Remote Sensing: ArcGIS, ENVI, Google Earth
Graphics/Design: SigmaPlot
Statistics: SYSTAT, SigmaStat
Word Processing: Word
Spreadsheets: Excel
Databases: Access

ASSOCIATIONS

- Society for Range Management
- International Association for Landscape Ecology
- Soil Science Society of America
- American Geophysical Union