THE PRESCRIBED BURNING IMPACTS ON SOIL WATER REPELLENCY AND SOIL HYDROLOGICAL PROPERTIES IN SAGEBRUSH-STEPPE ECOSYSTEM

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Abstract

Prescribed fire is an important tool for rangeland management in sage-steppe ecosystem, yet the long-term effects of this practice have not been well studied. Previous studies of fire-affected soil water repellency have identified the strength and persistence of SWR after burning in different types of forests but have not identified consistent timelines for post-fire recovery. This study explores the impacts of fire and plant community succession on SWR and infiltration properties to further inform rangeland managers regarding the long-term impacts of prescribed fire on SWR and infiltration properties in sagebrush-steppe ecosystems.

The objectives of this study were: 1) To explore the temporal effects of prescribed burning in a sagebrush-dominated landscape; 2) To investigate spatial variability of soil hydrologic properties with changes in plant cover (aspen, big mountain sage and low sage) and soil texture; 3) To determine relationships among soil organic fractions, soil hydrophobicity and infiltration properties.

Fieldwork was conducted in paired watersheds in the Northwest Watershed Research Center at Upper Sheep Creek (USC) and an unburned adjacent watershed Wood Gulch Creek (WGC), southwest of Boise, Idaho. These two watersheds are very similar in that they have three dominant vegetation cover communities: Low Sage, Big Mountain Sage and Aspen, similar elevation and topography. They differ in that USC is a long-term enclosure from cattle grazing and the site of a prescribed fire, while WGC watershed is open to cattle grazing and has not burned in recent history. Prior measurements of pre-burn and post-burn infiltration tests and Water Drop Penetration Time (WDPT) at USC
were extended in this study. Several analysis methods were used to calculate hydraulic conductivity, sorptivity and Water Repellency Index (WRI). Additionally, ten replicate soil samples of 15 cm depth were cored from each transect and used to analyze the fraction of organic matter and the static water-soil contact angle.

The recent analyses showed that the severity and occurrence of surface soil water repellency was substantially reduced eight years after fire treatment within the area originally covered with big sage, where the fire intensity were greatest. Also, hydraulic conductivity significantly increased in each vegetation cover type over the eight-year period of study. The comparisons among soil hydrological properties shows that hydraulic conductivity is not directly related to SWR, and sorptivity is inversely related to WRI in a general sense. The spatial variability in conductivity is primarily controlled by soil texture, whereas sorptivity is affected by soil organic content and soil wettability. The frequency of SWR was least in Low Sage and greatest in Aspen, reflecting a significant difference in soil organic content. Measurements of static water contact angle and organic content analysis show a strong positive correlation, primarily for Aspen and Big Sage sites. However, many soil samples from Big Sage and Aspen sites had substantial organic matter yet were not hydrophobic. It is concluded that soil organic matter content is not well correlated to SWR at microsite scale but may applicable as general indicator of infiltration capacity or SWR at larger scale within similar soils and vegetation type. The increased infiltration capacity eight years after fire at USC Low Sage indicates a long-term benefit of prescribed fire for increased fodder production and runoff management in semiarid rangeland.
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AND SOIL HYDROLOGICAL PROPERTIES IN SAGEBRUSH-STEPPE
ECOSYSTEM

by

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It is my third year in Syracuse University and the time of three-year story is going to end with the completion of the thesis. The thesis not only represents my work at keyboard but also includes the efforts from people who helped me and offered many kinds of support.

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Chapter 1-Introduction

1.1 Prescribed Fire in Rangeland Management

Fire has been recognized for centuries as a useful tool for managing rangeland plant communities in sage-steppe ecosystems (Young et al., 1983; Ortmann, 1998; Bates and Davis, 2014; et al). At present, a range of sectoral interests have various objectives for rangeland management. For instance, government-managed rangelands seek to preserve or enhance biodiversity and cultural heritage, whereas pastoral lands are chiefly managed for resource harvesting and animal production. Prescribed fire is designed to meet the goals of stakeholders who aim to remove woody vegetation, maximize biodiversity, and protect fire-sensitive habitats or culturally significant sites, whereas fire has associated risk in areas of intensive agriculture and higher population density.

Fire is a double-edged sword in sagebrush ecosystems. If the primary goal is to preserve and restore sagebrush landscape and wildlife, prescribed fire may not be applicable in land management. After burning, the dominant sagebrush (e.g. *Artemisia tridentata*) is replaced by more palatable herbaceous species and likely to recover slowly (Ralphs and Busby, 1979). Meanwhile, establishment of invasive grasses such as cheatgrass (*Bromus tectorum*) often accelerates the fire cycle through further invasion of non-native species into the fragmented remaining stands of sagebrush (Whisenant, 1990; Knick 1999). Also, the loss of sagebrush generally represents the loss of original important wild habitat (Miller, 2000; Welch, 2003). However, prescribed burning may be a desirable treatment if improving livestock production is the main goal.

Fire also exerts significant influence on soil hydrological characteristics (Huffman,
burning has been reported to increase hillslope- and watershed-scale runoff and erosion by several orders of magnitude (Malmon, 2007; Larsen, 2009; De Dios, 2005; Scott, 1993). It is well documented that these factors of fire contribute to increased runoff and erosion: removal of protective vegetation and litter cover (King, 1981; Johansen, 2001; Pannkuk, 2003); soil sealing by ash particles (Etiegni, 1991); reduction of soil particle size and breakdown of aggregates (Scott, 1993); and soil water repellency (DeBano, 2000a). Thus, the use of prescribed fire requires consideration of both economic and environmental effects.

1.2 Soil Water Repellency

Soil water repellency, or hydrophobicity, occurs in natural soil and fire-affected soil throughout the world and may persist over time scales ranging from seconds to weeks (Doerr, 2000a; Dekker, 2005). Soil water repellency (SWR) has been of increasing interest to scientists and land managers over the past century due to its effects on hydrological processes such as hydraulic conductivity and infiltration capacity. It can lead to overland flow and ponding, accelerating erosion and soil degradation, and thereby detrimentally affect seed germination and plant growth.

The first description of water repellency in soil was recorded by Schreiner (1910), but intensive research of SWR was limited until the 1960s. Studies of SWR have focused on fire, soil organic matter, land management and amelioration strategies (DeBano, 1981). More recently, researchers have acknowledged that SWR is more widespread than previous understood (Wallis and Horne, 1992, Doerr, 2000) and the effects of SWR have been addressed as a factor for use in hydrological modeling (Doerr, 2006b; Bachmann,
Despite these advances, the complexity of the spatial and temporal factors affecting soil hydrophobicity continues to challenge quantification of the effects of fire on SWR and potential impacts on infiltration and runoff on sagebrush-dominated landscape.

1.2.1 Major Factors Affecting Soil Water Repellency

**Organic Matter**

It is commonly accepted that water repellency is caused by organic compounds (Doerr, 2000a). Schreiner (1910) originally suggested that SWR was caused by waxes. Many investigations were conducted to identify the specific organic compound leading to SWR (Franco, 1994; McIntosh, 1994). Doerr (2000a) summarized that organic compounds which were identified as precursors to water repellent soil can be divided to two groups. The first is aliphatic hydrocarbons, which contain carbon and hydrogen joining together in branched chains or non-aromatic rings. These non-polar substances are nearly insoluble in water. The second group is substances with polar structure which are soluble in water. The soil is water repellent if coated by the substances in the first group, and soil can be either hydrophobic or hydrophilic if it is coated by substances of the second group, depending on the orientation of the functional group towards the soil surface. The orientation is affected by temperature, pH, moisture and physical disturbance.

Many hydrophobic compounds have been extracted in previous studies such as fatty acids, amides, alkanes, aldehydes/ketones (Mainwaring, 2004), alkanols (Hansel, 2008), lipids and humic acids (De Blas, 2010). Although many chemical substances in soil have been identified, the interaction between various compounds and soil remains unclear due
to their abundance in nature. Despite a rich literature in the chemistry of hydrophobicity, SWR is less understood at the molecular to soil aggregate scale.

Vegetation is the primary source of soil organic matter. Rodriguez-Alleres et al. (2007) compared water repellency of soils under cropland and forest. They found that most soil under corn and grass were not generally water repellent but forest topsoil showed extraordinary water repellency. They concluded that soil water repellency of forest was due to high organic content. This finding supports the view that evergreen trees are most common plants associated with soil water repellence. In particular pines and eucalyptus are noted to produce copious volumes of hydrophobic compounds including waxes, resins and aromatic compounds (Scott, 1992; Moore and Blackwell, 1998; Doerr, 1996).

Soil microbes may also affect SWR through creation of hydrophobic substances that coat soil particles. Fungi such as *Penicillium nigrican* and *Aspergillus sydowi* have been associated with SWR (Savage, 1972). Biofilm, including extracellular polymeric substances (EPS), also can induce SWR (Schaumann, 2007). Yet isolating specific hydrophobic compounds from the complex mixture of EPS and detritus in SOM to characterize the controls on SWR, is likely to remain a challenge for the foreseeable future (Wang, 2000).

The amount and type of organic matter and its relationship to SWR are complex and attempts have been made to establish a predictive method or relationship between organic matter or organic content and the degree of soil hydrophobicity. However, the results have not been consistent. McKissock (1998) found a positive relationship between SWR represented by Water Drop Penetration Time (WDPT) and organic matter content. Wallis (1993) concluded that the organic carbon content of the Waitarere sand was not related to
water repellency tested by molarity of ethanol dilution (MED). There are two possible explanations for this apparent contradiction: the amount of organic matter that causes water repellency is not proportional to the actual amount of organic matter present in the soils, particularly if different type of soils or different conditions of soil are compared; or the different tests of SWR may show different results. In a study by Dekker (1994), organic matter content was positively correlated with MED, whereas it was not significantly related to WDPT.

Fire

Fire is an important non-biological factor influencing SWR and other soil properties. Intensive studies have been conducted for fire impacts under different vegetation types such as semi-arid rangeland (Salih, 1973; Pierson, 2001; Pierson, 2008), chaparral (Hubbert, 2006), and forest (Doerr, 2009; Huffman, 2001; Leiws, 2006). The fire impacts involve severity of water repellency, longevity of soil hydrophobicity, infiltrability, soil structure and soil moisture.

The magnitude of change to soils following a fire depends on burn severity. In an area with low-severity fire, fine fuels such as surface litter and small woody debris are burned, but larger fuels may not be consumed. Soil heating is minimal and result in only minimal mineral soil exposure (Wells, 1979). However, high-severity fire usually consumes most surface litter and plants, exposes mineral soil, disturbs soil structure (Moody, 2001; DeBano, 2000b) and generates a steep temperature gradient in the top 2-3 cm of soil (Robichaud, 2000; DeBano, 1979). Savage (1974) concluded that heat produced by burning vaporizes organic substances and drives them downwards along the temperature gradient. As the vaporized substances condense and coat mineral soils, a fire-
induced water repellent layer under the burned area is created (DeBano, 2000b). Thus, the incipient water repellency may not change when soils are heated to less than 175 Celsius, but intensive water repellency is formed when soil temperature increases to 175 and 200 Celsius (DeBano, 1981). The severity of water repellency increases with temperature until approximately 300 Celsius, when organic compound that are precursors to water repellency degrade.

Comparatively little is known about the persistence of water repellency after burning and the results of existing long-term studies vary. Dyrness (1976) studied fire-induced water repellency on coniferous forest and found water repellency persisted for as long as six years in coarse-textured soils ranging from loamy sand to sandy loam. MacDonald (2004) concluded that fire-induced water repellency in coarse-textured soil under predominantly Ponderosa (*Pinus ponderosa*) and lodgepole (*Pinus contorta*) pine forest gradually weakened to nearly undetectable levels within 1 year after burning. Given the study of persistence of soil water repellency after fires in the Colorado Front Range, Huffman (2001) indicated that severity of fire, soil moisture and percentage of sand were primary controls over fire-induced soil hydrophobicity there.

**Natural Soil Water Repellency**

The properties of unburned soils also result in widespread occurrence of SWR (DeBano, 1981; DeBano, 1991). Soil texture, for example, has been associated with the strength of soil water repellency. Numerous studies have reported that SWR appears more frequently in coarse-textured soil than soils with high clay content (McKissock, 2003; Roberts, 1972; McGhie, 1981). Due to the smaller surface area per unit volume of sand compared to finer texture soils, coarser soils have a relatively greater chance to bond with
hydrophobic substances (DeBano, 1981; Blackwell, 1993). For this reason, Australian farmers often add clay to sandy soils to mitigate water repellency (Bond, 1969).

However, soil texture is not a strong predictor of the occurrence of water repellency. Scott (2000) found that some fine textured soils in South Africa were highly water repellent suggesting that texture may not be a significant predictor of water repellency. Many studies have also reported that water repellency occurred in fine-textured soils contained more than 20% to 40% of clay (McGhie, 1980; Giovannini, 1983). Doerr (2000a) proposed that, in some circumstance, fine-textured soils could be more water repellent than coarser soils because hydrophobic substances are of sufficiently high concentrations within the soil matrix that hydrophobic substances formed a larger total area of water repellency.

Soil moisture conditions can influence water repellency. Drier soils tend to be water repellent (King, 1981) and soils are no longer water repellent once wetted (Doerr, 2000b). Huffman (2001) showed that soil water repellency significantly decreased with increasing surface soil moisture. The identification of seasonal variability in the presence and strength of soil water repellency supports the observation that SWR is usually low or absent in prolonged wet seasons and more severe in dry periods (Ristema, 1994).

1.2.2 Determination of Soil Water Repellency

Soil hydrophobicity can be measured by several field and laboratory techniques. Common methods include Water Drop Penetration Time (WDPT), (Roberts, 1971), the Molarity of Ethanol Droplet (MED) test (Dekker, 1994), contact angle measurement (Bachmann, 2003) and the Water Repellency Index (Pierson, 2001).
The WDPT test is the most common and simplest method for measuring the presence and the degree of soil hydrophobicity in the field. The test is conducted by placing a water droplet on the soil surface and recording the time required for the droplet to completely infiltrate into the soil, which is related to SWR. Differences in the methods and standards used by various investigators make direct comparison of results difficult. For example, various time standards have been reported to indicate a threshold SWR, including 1s (Roberts et al., 1971), 5s (Bisdom et al., 1993) or 60s (Walsh et al., 1994). Secondly, the validity of the WDPT depends on maintaining a constant or advancing angle of incidence greater than 90 degrees with the test surface, and can be confounded by atmospheric conditions that promote evaporation, which reduces drop diameter and contact angle. Furthermore, the WDPT does not have physical meaning and is readily affected by surface roughness and pore geometry (Wessel, 1988). Thus, although WDPT is very useful for determining the presence of water repellency, it is a somewhat subjective method to determine the degree of soil hydrophobicity. However, the simplicity of this method makes it a useful discriminator for hydrophobic and hydrophilic soils and an approximate indicator of the degree of soil water repellency.

The contact angle is defined as the angle intersected by liquid-solid surface and liquid-gas surface, which is measured as the tangent from the contact point along the liquid-gas interface. The three phase contact angle is a common measure of the wettability of a surface. The wettability of a liquid is function of surface tension or free energies between liquid-solid-gas interfaces. Young (1805) proposed an expression relating the contact angle and interfacial energies as shown as equation 1. A liquid with low tension will spread over a solid surface and smaller contact angle occurs. A complete wettability
of solid surface in contact with liquid and gas phase occurs contact angle at zero degrees (Letey, 1962).

\[ \cos(\theta) = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \]  

Eq.1

Where \( \theta \) is the contact angle, \( \sigma \) is the surface energy, and \( s, v \) and \( l \) represent the solid, gas and liquid phase, respectively.

Figure 1.1 shows that a contact angle between a water droplet and a solid surface is less than 90° for a wettable surface and greater than 90° for non-wettable surface. Increasing contact angle greater than 90° is associated with decreasing wettability of the surface. Ideally, a completely non-wettable surface would have a contact angle of 180°.

**Figure 1-1 Illustration of contact angle of a drop on wettable and non-wettable surfaces**

Contact angle measurement is affected by surface roughness (Philip, 1971), surface chemical heterogeneity (Dettre, 1964), the liquid used and length of contact time. A rough surface and a high degree of chemical heterogeneity may lead to the phenomenon known as geometric deviation (Chibowski, 2002). Similarly, liquid composition affects surface tension contact angle hysteresis, with larger contact angles observed in an advancing wetting front and smaller contact angles in a receding wetting front (Bachmann, 2003).

The Molarity of an Ethanol Droplet (MED) test or “Critical Surface Tension” test can
be considered as an extension of WDPT. This method indirectly measures the apparent surface tension of a soil surface by using different concentration of ethanol. The MED quantifies the hydrophobicity as the lowest concentration of ethanol in water that is infiltrated into soil within 5 s (Dekker, 1994). Usually, the concentrations of the ethanol solutions prepared for the test range from 0% to 36% (Dekker, 2009). Although MED can also be used to classify the relatively severity of water repellency in soils, Doerr (2000b) suggested that they are not well related to the actual wetting behavior.

The Water Repellency Index (WRI) (Pierson, 2001) or Infiltrability Index (INI) (Pierson, 2008) is used to quantify the impact of soil water repellency, whether the SWR occurred in nature or was induced by fire. The difference between infiltration on wettable soil and water repellent soil can be assessed by comparing the rates of infiltration early and late in a rainfall simulation test. The infiltration rate for water repellent soil is retarded during early stages and gradually increases to a final steady infiltration rate (Robichaud, 2000). The opposite process occurs in water repellent soil the infiltration rate is rapid at the beginning and tends to decrease in a steady state. Thus, WRI is developed to assess the impact of SWR in terms of infiltration tests.

1.3 The Effects of Fire-Induced Water Repellency on Hydrological Process

Previous studies have observed various wetting patterns during infiltration under different soil conditions (Dekker and Ritsema, 2000; Ritsema and Dekker, 2000; Ritsema, 1998; Bughici, 2016). In the study of Ritsema (1998), infiltration under ponding in dry, water repellent soil tended to form unstable wetting fronts such as finger flow. Infiltration in high water repellent soil formed perturbed wetting fronts instead of preferential paths.
Bughici (2016) found three wetting behaviors of infiltration in wettable soil and various degrees of water repellent soil. The wetting plume in wettable soil expanded laterally and vertically by capillary flow and soil saturation decreased uniformly with the radial distance from the point source. Conversely, for the slightly water repellent soil, the saturation changed abruptly from high to low at the edge of plume and the resulting negative saturation gradient was generated from core plume to surrounding annulus. In strongly repellent soil, the wetting front expanded laterally more than vertically and patchy saturation occurred.

Many studies have reported that fire-induced water repellency leads to the reduction of infiltration capacity and results in overland flow and soil erosion (Dekker and Ritsema, 2000; Pierson, 2002; et al). Martin (2001) compared the soil infiltration rates in burned and unburned sites and concluded that there was a significant difference in infiltration rates between burned and unburned areas of volcanic soil with various vegetation. Pierson (2001, 2008) investigated the temporal dynamics of fire-induced water repellency on rangeland hydrology and found that burned shrub coppice had significantly lower rates of infiltration compared to unburned sites. This difference gave rise to an associated increase in runoff and sediment from study plots. However, the impact of fire on infiltration rates was not significant 1 year after the fire. In an extension to that study, Pierson (2008) found that inter-annual variability and intensity of water repellency and ground cover removal exerted greater influence on runoff and erosion than the impact of fire.
1.4 Objective

The objective of this project is to understand the long-term effect of prescribed burning on soil hydrologic properties in a sagebrush-steppe ecosystem. Prior studies of the persistence of fire-induced water repellency do not provide consistent results across rangeland sites. Reports of the duration of post-fire SWR range from six years in coniferous forest (Drymess, 1979), to one year in pine forest (MacDonald, 2004). Pierson (2001) showed that SWR was reduced within a year after fire. Long-term observations of SWR persistence following rangeland fire in rangeland have rarely, if ever been reported.

In the study of sagebrush-dominated landscape, Pierson (2001) showed the short-term impact of wildfire on hydrological response including infiltration rate and runoff. At plot scale, for example, coppice microsites had very uniform fire-induced soil water repellency. Infiltration rate significantly decreased and sediment increased after one year. Yet, little is known regarding whether hydraulic conductivity, sorptivity and the coupled processes affecting infiltration rate, are associated with fire induced water repellency.

Organic matter is a primary cause of SWR, with lesser factors such as soil texture and soil water content adding complexity to its prediction. It is difficult to isolate the individual factors in field tests to quantify the effect of this factor on SWR. Although there are also many research studies on the hydrophobicity of specific organic compounds, the molecular scale of hydrophobicity in natural soils remains poorly understood due to the complex interaction among soil structure, soil surface chemistry, and site climate. Previous studies that investigated the relation between soil organic content and SWR showed inconsistent results. McKissock (1998) found a positive relationship between SWR and organic matter content for fine-textured soils. Wallis (1993) concluded that the
organic carbon content of the Waitarere sand was not related to water repellency. Studies of SWR in silt loam soils are limited in the literature, and are required to understand the hydrologic functional response to fire on sage-steppe ecosystems, which commonly occur on silt loam soils.

The goals of this research are:

1) To explore the temporal effects of prescribed fire in a sagebrush-steppe landscape;
2) To investigate spatial variability of soil hydrologic properties before and after fire;
3) To determine relationships among soil organic fraction, water repellency assessment methods and infiltration properties
2 Chapter 2-Study Area

The research was conducted in two catchments within the US Department of Agriculture Northwest Watershed Research Center, located at Reynolds Creek Watershed in southwest Idaho. Baseline data on soil and infiltration properties were collected in the Upper Sheep Creek catchment prior to prescribed fire in August 2007 and shortly after the fire in October 2009. This study expands the data set by repeating those surveys eight years after fire, in June 2015, and making supplemental measurements of soil properties at both Upper Sheep Creek catchment and the adjacent, unburned Wood Gulch Creek catchment.

Upper Sheep Creek is a 26-ha semi-arid rangeland watershed at an elevation of 1835 to 2049 meters within the Reynolds Creek Experimental Watershed (RCEW) in the Owyhee Mountains of southwest Idaho, USA (Marks, 2001). The watershed is managed by the USDA-ARS Northwest Watershed Research Center. Average annual precipitation is approximately 426 mm, most of which is snow (Chauvin, 2011). Historically the streamflow was primarily derived from snowmelt with an average annual yield of nearly 44 mm, although the rain to snow fraction of precipitation has increased in recent decades (Nayak et al, 2009). The distribution of precipitation at the site exhibits great spatial variability due to interactions between wind direction and topography (Winstral and Marks, 2002) with associated patterns in soils and vegetation. Soils are primarily silt loam and vary in depth up to 3 m in drift areas (Table 2.1). The underlying geology consists of
variably fractured and altered basalt underlain by thick, dense basalt at a depth of 20-30 m (Flerchinger, 2000). Previous geological studies have indicated that the surface of the dense of basalt flows the surface topography, thus the watershed boundary for ground water flow is possibly similar to surface (Winkelmaier, 1987; Mock, 1988). Wood Gulch Creek watershed is adjacent to USC and has analogous patterns in topography, precipitation, soils and vegetation (Figure 2.1).

Table 2-1 Soil series name and family classification mapped in USC and WGC. Natural Resources Conservation Service, United States Department of Agriculture, Official Soil Series Description.

<table>
<thead>
<tr>
<th>Soil Series Name</th>
<th>Family Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabica</td>
<td>Loamy-skeletal, mixed, superactive, frigid lithic argixerolls</td>
</tr>
<tr>
<td>Harmehl</td>
<td>Fine-loamy, mixed argic pachic cryoborolls</td>
</tr>
<tr>
<td>Demast</td>
<td>Fine-loamy, mixed, superactive Pachic Argicryolls</td>
</tr>
<tr>
<td>Nettleton</td>
<td>Fine, smectitic, frigid Argiaquic Xeric Argialbolls</td>
</tr>
</tbody>
</table>

The dominant vegetation types for the study watersheds are Aspen (*Populus tremuloides*), Mountain Big Sagebrush (*Artemisia tridentata*), and Low Sagebrush (*Artemisia arbuscula*) (Figure 2.1). There are other subordinate vegetation species mixed in the different landscapes. Grass (*Poaceae*), forb and snowberry (*Symphoricarpos*) are observed in the Big Sagebrush areas. Snowberry and grass are also observed under the canopy in the Aspen areas. In the Low Sage areas, few other plants are observed.

Detailed descriptions of USC and WGC are provided in previous study (Flerchinger, 1998; Flerchinger, 2000) and summarized as follows. The low sage area has sparse low sagebrush with some sandberg bluegrasses (*Poa secunda*) and considerable bare ground. The soil profile is generally shallow, around 30 cm to basalt bedrock, and consists of a relatively high clay content argillic horizon and thin loamy surface layer. Snow cover was
reported less than 60 cm for most of winter. The mountain big sage area is mostly covered by big mountain sagebrush, snowberry and a few grasses. The soil profile is typically greater than 100 cm to basalt bedrock, deeper than low sage area. It has less argillic properties and a thick surface loamy layer around 50-100 cm. Snow typically accumulates up to 1 m during winter. The aspen area has a complete cover of aspen and understory vegetation such as sagebrush and grasses. The soil profile is very deep, often greater than 200 cm to bedrock. Argillic horizons are typically absent and the soil is almost entirely comprised by loamy sand. Snow cover depth varies from 1 m to more than 8 m. The snow drifts into aspen and big sage areas each winter and persists until snow has disappeared from the rest of the watershed.

There are two major differences in management between these watersheds: USC was fenced to exclude grazing in 1970 while grazing has been intermittent at WGC. Secondly, USC was burned, and WGC was not.
Figure 2-1 Vegetation distribution on Upper Sheep Creek (USC) and Wood Gulch Creek (WGC). Each 30.5 m transect over the dominant vegetation cover classes: Aspen (A), Mountain Big Sage (BS) and Low Sage (LS). Source: http://criticalzone.org/reynolds/data/dataset/3934/
Figure 2-2 Soil distribution on USC and WGC and the 30.5 m transect of each dominant vegetation cover at USC and WGC. Source: http://criticalzone.org/reynolds/data/dataset/3934/
3 Chapter 3-Methods

To make comparative measurements across vegetation type and management, three transects, each 30.5 m in length were established in both watersheds across well-developed patches of aspen, big mountain sage and low sage. The 30.5 m linear transects are aligned with the prevailing wind direction to capture the greatest range of soil water input within a site and the greatest similarity in that range between replicate sites. Field measurements were made at 60 cm intervals to determine unsaturated hydraulic conductivity, sorptivity, water drop penetration time, and water repellency index. Soil samples were taken at approximately 3 m intervals for laboratory determination of sessile drop soil-water contact angle and soil organic carbon (SOC) and nitrogen (N) content.

3.1 Infiltration

3.1.1 Materials

Automated Mini Disk Infiltrometers (AMDI) were used in this study for infiltration testing. This method has advantages in automated data collection, portably use, replication and its simplicity of operation on various surfaces and slopes (Madsen and Chandler, 2007; Valinski and Chandler, 2016) and is based on the design of Decagon Inc. (Pullman, WA). The schematic design of an AMDI is shown in Figure 3.1. The differential pressure transducer (SenSym ASCX01DN, Honeywell, Freeport, IL) measures the difference in pressure between the headspace at the top of the reservoir tube and the pressure at the base of the polyethylene straw to determine the rate of change in the stored volume. The reservoir tube has a volume of 96.7 cm$^3$, a height of 18 cm and an inside
diameter of 2.52 cm. The porous disk attached at the bottom of the reservoir tube has a diameter of 3.2 cm. There is air inlet capillary tube above 10 mm of the bottom controlling the tension for water against gravity. In laboratory testing, the average bubbling pressure of the air inlet capillary is 3.5 cm±0.5 cm. The device is filled by submerging the base of the infiltrometer in water and gently removing air by suction through a one-way valve in the rubber stopper to a standard fill depth. The transducer output voltage is recorded by a four channel data logger with a Data Logging Shield (Adafruit Industries) on a SD card. This assembly is housed in a sealed case and powered by a 6V power supply. The data logger program was compiled with the Arduino code and logs data at one-second intervals onto a standard SD card. (https://dgchandl.expressions.syr.edu/devices/portable-infiltrometer-logger/).

Figure 3-1 Schematic illustration of an automatic mini disk (Madsen and Chandler, 2007)

Stevens HydraProbe is used to measure soil moisture and soil temperature. Any mobile device with the free HydraMon application can receive data wirelessly from the
HydraProbe by wifi. Simply insert the probe into the soil and tape on “Sample” button in the HydraMon app. The app will immediately display a series of parameters on-screen such as soil moisture content, temperature and conductivity.

3.1.2 Field Experimental Design

A series of unsaturated infiltration tests were made and soil samples were taken in the summer of 2015 at Upper Sheep Creek and the adjacent Wood Gulch Creek watersheds. Linear transects 30.5 m in length were defined in the three dominant vegetation types: low sage, big mountain sage and aspen (Fig.2.2). Fifty infiltration measurements were made in each transect at 0.6 m intervals under a dry initial condition. The measurement was conducted under a dry initial condition for USC. However, the initial condition varied in WGC due to a small rain event occurred prior to measurement. At each measurement location, silica sand was first placed on the soil surface provide a regular contact surface at the disk-soil interface. Figure 3.2 shows a top down view of an infiltration test conducted at Low Sage transect. The initial soil moisture and temperature were measured in the adjacent soil prior to each infiltration test. Final measurements of soil moisture and temperature were made at the point of the infiltration test to determine changes in water content and the temperature of the soil after infiltration. Some locations in the Low Sage transect had high gravel content that impeded this measurement. In this case proxy data were obtained from adjacent measurement locations.
3.1.3 Determination of Hydraulic Conductivity and Sorptivity

Infiltrometer data were collected at 1 second intervals for twenty to 40 min. The recorded records of sensor voltage were related to the water column height in the reservoir tube, and converted to volumetric units for infiltration calculations by equation 2, following Madsen and Chandler (2007).

\[
V(t) = V_{tot} \left[ 1 - \frac{v_0(t) - v_{\min}}{v_{\max} - v_{\min}} \right] \tag{Eq.2}
\]

Where

\( V_{tot} \) is total volume of water in the infiltrometer reservoir,
\( v_{\text{max}} \) is maximum voltage at the beginning of each trial measurement, 
\( v_{\text{min}} \) is the voltage at the end of measurement, 
\( v_0(t) \) is voltage at time \( t \), and 
\( V(t) \) is the volume of water has been infiltrated at time \( t \).

The method of Zhang (1997) was used to estimate the values of hydraulic conductivity and sorptivity in this study by cumulative infiltration, \( I \):

\[
I = C_1 t + C_2 \sqrt{t} \quad \text{Eq.3}
\]

Where \( C_1 \) (m s\(^{-1}\)) and \( C_2 \) (m s\(^{1/2}\)) are parameters which are related to hydraulic conductivity, \( K(h) \) and sorptivity, \( S \). The relations are:

\[
K(h_0) = C_1 / A_1 \quad \text{Eq.4}
\]

\[
S(h_0) = C_2 / A_2 \quad \text{Eq.5}
\]

Where \( A_1 \) and \( A_2 \) are one-dimensional coefficients to be determined using the Van Genuchten (1980) retention function for a soil:

\[
A_i = \frac{11.65(n^{0.1} - 1)\exp\left[2.92(n-1.9)\alpha h_0\right]}{\left(\alpha r_0\right)^{0.91}} \quad \text{for } n \geq 1.9 \quad \text{Eq.6}
\]

\[
A_i = \frac{11.65(n^{0.1} - 1)\exp\left[7.5(n-1.9)\alpha h_0\right]}{\left(\alpha r_0\right)^{0.91}} \quad \text{for } n < 1.9 \quad \text{Eq.7}
\]

\[
A_2 = 1.4b^{0.5}(\theta_i - \theta_f)^{0.25}\exp\left[3(n-1.9)\alpha h_0\right] / \left(\alpha r_0\right)^{0.15} \quad \text{Eq.8}
\]

Where \( n \) and \( \alpha \) retention parameters based on soil texture; \( h_0 \) (≤0) is the pressure head of the infiltrometer (-3.5 cm) in this case; \( \theta_i \) and \( \theta_f \) are the initial and final soil moistures; \( r_0 \) is the radius of the infiltrometer; and \( b \) is arbitrarily set to 0.55 (Warrick and Broadbridge, 1992). Soils with high sand content have values of \( n \) greater than 1.9 and use equation 5; soils with more clay have lesser values of \( n \) and use equation 6. The
summary of values of n, α and other parameters based on soil texture are presented in Table 3.1. In this study, the main soil texture in research is sandy loam.

**Table 3-1 Typical values of Van Genuchten parameters (α and n) for various soils**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>α (cm⁻¹)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.145</td>
<td>2.68</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>0.124</td>
<td>2.28</td>
</tr>
<tr>
<td>Loam</td>
<td>0.036</td>
<td>1.56</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>0.075</td>
<td>1.89</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>0.02</td>
<td>1.41</td>
</tr>
<tr>
<td>Sandy Cl. Loam</td>
<td>0.059</td>
<td>1.48</td>
</tr>
<tr>
<td>Silty Cl. Loam</td>
<td>0.01</td>
<td>1.23</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>0.019</td>
<td>1.31</td>
</tr>
<tr>
<td>Silt</td>
<td>0.016</td>
<td>1.37</td>
</tr>
<tr>
<td>Clay</td>
<td>0.008</td>
<td>1.09</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>0.027</td>
<td>1.23</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.005</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Based on the calculation of cumulative infiltration, C₁ and C₂ are obtained by fitting the curves to graphs of cumulative infiltration, I, versus time and the square root of time, respectively. In the early stage of infiltration, the capillary force driving infiltration is represented as sorptivity. As the wetting front moves further from the disk, flux approaches the unsaturated hydraulic conductivity at the defined suction head (-3.5 cm). Thus, the early time infiltration data can be used to fit sorptivity and the late time data can be used to fit hydraulic conductivity: C₂ is thus obtained by plotting cumulative infiltration versus the square root of time (Figure 3.3) and fitting the data to a second-order polynomial equation, 0.007 in the case of Figure 3.3. The value of C₁ can be obtained by plotting cumulative infiltration versus time (Figure 3.4) and fitting the data to a first-order polynomial equation, 0.0038 in the case of Figure 3.4. The data of these
3.2 Determination of Soil Water Repellency

3.2.1 Water Drop Penetration Time

The WDPT test is a useful indicator of occurrence of SWR, although it is an
approximate method. WDPT tests were conducted at the mineral soil surface adjacent to transect locations used for the infiltration tests. Vegetation and surface litter were removed by hand prior to conducting the test. The WDPT test was performed by placing one drop of distilled water on the soil surface and recording the time required for the drop to completely infiltrate the soil. In this study, three classes of WPDT were used to assess the severity of water repellency at the mineral soil surface: 0-4s as wettable; 5-59s as water repellent (Hydrophobicity I); and greater than 60s as strongly water repellent (Hydrophobicity II).

3.2.2 Water Repellency Index

The Water Repellency Index is used to determine the influence of SWR in terms of infiltration. The WRI was calculated for each infiltration test using the following equation (Pierson, 2001):

\[
WRI = \frac{i_{\text{fin}} - i_{\text{min}}}{i_{\text{fin}}} \times 100\% \quad \text{Eq. 9}
\]

Where \( i_{\text{fin}} \) is the final infiltration rate measured at the end of infiltration which is in steady rate and \( i_{\text{min}} \) is the minimum infiltration rate throughout the entire infiltration.

3.3 Soil Sampling and Elemental Analysis

3.3.1 Soil Sampling and Preparation

Measurements of soil organic carbon and nitrogen content were compared for 100 paired samples randomly selected from the collected soil cores to identify any difference between preparation 1 by grinding and drying at 78 Celsius, and preparation 2 by sieving
and drying at 55 Celsius. Ten soils (15 cm depth) were extracted by soil core sampler (AMS Inc., American Falls, ID, USA) along each transect and stored in polythene tubes. Soil samples collected from the field were stored on ice at the field site prior to transportation, stored in refrigeration, shipped to laboratory within a week and stored in cold room at 5°C. The 15 cm soil cores were separated into three parts (0-5 cm, 5-10 cm and 10-15 cm) and oven dried in open containers at 40 Celsius for seven days. Temperatures over 50 Celsius can volatize organic compounds and result in losses of carbon and other nutrients (Boone et al. 1999). The dried samples were stored in HDPE containers.

Methods of preparing samples of field soils for laboratory analyses vary. To evaluate the effects of soil granule size and dry temperature, two preparations for soil organic carbon (SOC) and total nitrogen (N) determination were made. In the first preparation, soil was forced through a 2-mm stainless steel mesh sieve to remove leaf litter and roots. Sieving served to remove gravel and woody debris and to homogenize the soil by breaking up the aggregates that can store organic compounds. All roots larger than 2 mm were removed with forceps, leaving darker pieces of decayed organic matter in the sample. Sieved samples were transferred to aluminum weighing dishes, and dried overnight in an oven at 55°C. In the second soil preparation, soil aggregates were ground and large roots and litter were picked out. The soil was dried overnight in aluminum weighing dishes, but at 78°C. Subsamples from both soil preparations were weighed and packed into 10.5 x 9 mm tin capsules for SOC and N analyses.
3.3.2 Contact Angle Measurement

A sessile drop goniometer (e.g., Bachmann, 2003) was constructed to measure the soil-water-air contact angle (Figure 3.5). The device consists of a horizontal plate, input syringe and microscope camera. Unlike traditional goniometers, which typically introduce the drop from a needle above the test plate, water was introduced to the surface from below via a needle that passed through the plate and the soil, in the center of a 2.5-cm diameter by 1-mm deep recession machined into the polycarbonate plate. This modification was made to minimize disturbance of the soil surface and contact angle by the needle. The same ground and air dried soils used in C/N analysis were sampled for use in the sessile drop goniometer. Each soil sample was placed as a cone around the elevated needle, then pressed with a brass disk into a planar surface even with the surface of the plate. The brass disk soil packer was designed to slide axially on the needle and was rotated on that axis to develop a smooth, compact surface. After the sample was prepared the needle was adjusted to approximately 1 mm above the soil surface. The water droplet was then introduced by a syringe and tube connected to the needle, while a camera continually captured images of the drop expansion over a period of 5s. The static contact angle on one side of each drop was determined by overlaying a goniometer scale (Figure 3.6). Theoretically, contact angles in the range from 90-180° can be observed. However, the applicable range of Sessile Drop Method is primarily limited by soil particle size (Bachmann, 2003). It was not possible to assess contact angles less than 90° because the water drops infiltrated the soil pad immediately. Contact angle measurements were obtained from the photographic images using graphic software (Adobe Systems, CA, USA).
Figure 3-5 The sessile drop goniometer and camera for contact angle measurement

Figure 3-6 Diagram of Determination for contact angle
3.3.3 Organic Carbon and Nitrogen Analysis

The C/N analysis was conducted with a Costech ECS-410 Combustion System. The wide range in SOM content required matching soil sample mass from the different vegetation classes to the machine detection range: approximately 20 mg of 0-5 cm soil from High Sage and Aspen and 50 mg of other soil samples. Quality Control (QC) samples were introduced throughout the analyses: Eight different masses of atropine, from 1 mg to 15 mg, were run as a calibration curve. Two Initial Calibration Verification (ICV) samples of Acetanilide were then analyzed following the calibration curve and prior to the soil samples. An Initial Calibration Blank (ICB) was set after ICV to identify any noise or background bias introduced by the combustion system. Thereafter, two Continuing Calibration Verification (CCV) samples of atropine and one Continuing Calibration Blank (CCB) were analyzed at a minimum of every ten soil samples and at the end of each run. The recommended order for the sample analysis is shown in Table 3.2. For standardization, an acceptable calibration curve required $R^2 > 0.9999$ and acceptable QCs required all analytes of interest to be within the calibration range and recovery values to be within ±10% of the true value. The compounds used as quality controls are summarized in Table 3.2.

Table 3-2 Composition compounds for quality control

<table>
<thead>
<tr>
<th>Compound</th>
<th>Nitrogen</th>
<th>Carbon</th>
<th>Hydrogen</th>
<th>Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atropine (C\textsubscript{17}H\textsubscript{23}NO\textsubscript{3})</td>
<td>4.84%</td>
<td>70.56%</td>
<td>8.01%</td>
<td>0%</td>
</tr>
<tr>
<td>Acetanilide (C\textsubscript{8}H\textsubscript{9}NO)</td>
<td>10.36%</td>
<td>71.09%</td>
<td>6.71%</td>
<td>0%</td>
</tr>
<tr>
<td>Soil 50019</td>
<td>-</td>
<td>4.4%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Apple leaves</td>
<td>2.25 %</td>
<td>47.6%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3.4 Data Analysis

3.4.1 Cumulative Frequency Diagrams

Cumulative frequency analysis was used to determine the cumulative distribution of properties. The cumulative frequency diagrams plotted using a frequency function in Excel. Cumulative frequency diagrams of sorptivity and hydraulic conductivity was used to compare the distribution of those properties before and after burning on USC and between USC and WGC.

3.4.2 Statistical Analysis

Simple linear regression was used in this study to investigate the relationship between contact angle and soil organic carbon. The relationship is defined by the formula \( y = a \cdot x + b \), where \( y \) = estimate dependent, \( x \) = independent variable, \( c \) = constant, \( a \) = regression coefficients. The coefficient of determination \( (R^2) \), was used as a measure of goodness of fit.

Descriptive statistics were used to calculate the mean, standard deviation and standard errors of soil moisture, soil temperature, soil organic carbon and nitrogen for each transect. These statistics provide the information about central tendency and variability of the data. The comparison between the results of two different soil preparations for C/N analysis was made using paired t test. Paired t test is applied to evaluate the difference between the two sample preparations. The null hypothesis assumes that the mean of two paired samples are equal:

\[
\mu_1 = \mu_2 \quad \text{Eq.10}
\]

Then calculate the difference \( (d_i = y_i - x_i) \) between the two observations on each
pair and calculate the mean difference, \( \bar{d} \), and the t value can thus be determined by:

\[
t = \frac{\bar{d}}{\sqrt{\frac{s^2}{n}}}
\]

Eq. 11

where

- \( s^2 \) is the sample variance,
- \( n \) is the samples size, and
- \( t \) is a paired t-test with \( n-1 \) degrees of freedom.

The level of significance was selected as 0.05, the critical value of \( t \) is 1.98 based on the \( t \)-distribution for a two-tailed test. The One-way ANOVA was used to determine whether there were any significant differences between the means of hydraulic conductivity, WRI, organic content among transects. The data for hydraulic conductivity, WRI and organic content passed the Kolmogorov-Smirnov test for normality. The one-way ANOVA was conducted using SPSS software. Based on the results of significance, the transects fell into one of the three group- a, b, and c.
4 Chapter 4-Results

This study includes four different approaches to assess the impact of natural SWR and fire induced changes in SWR on three vegetation cover types typical of sagebrush steppe ecosystems. Hydraulic conductivity, sorptivity and WRI are calculated from infiltration tests and used to identify temporal and spatial differences in these soil hydraulic properties between the land cover types and treatments. A large sample of WDPT tests from 2007 and 2015 are compared to explore the long-term effect of prescribed fire on the presence of SWR at USC. Laboratory measurements of soil water contact angle and SOC over a shallow (15 cm) vertical profile are compared to identify differences in shallow soil SOC between the replicate burned and unburned watersheds. Finally, the results of these analyses are compared in order to determine relationships among infiltration properties, soil organic fraction, and soil hydrophobicity within and across the treatments in this study.

4.1 Hydraulic Conductivity and Sorptivity

The analyses of hydraulic conductivity and sorptivity from 2015 included 201 points of measurement, after excluding data outliers due to infiltrometer malfunction (disfunctional air entry tube; malfunction of one-way valve; transducer failed to record data). Detailed information on the numbers of available measured points in 2007, 2009 and 2015 is provided in Table 4.1.
### Table 4-1 Detailed available points in each transect measured at 2009 and 2015

<table>
<thead>
<tr>
<th></th>
<th>Pre-burn sites at 2007</th>
<th>After-burn sites at 2009</th>
<th>Post-burn sites at 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>USC Low Sage</td>
<td>88</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>USC Big Sage</td>
<td>81</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>USC Aspen</td>
<td>85</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>WGC Low Sage</td>
<td>-</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>WGC Big Sage</td>
<td>-</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>WGC Aspen</td>
<td>-</td>
<td>-</td>
<td>35</td>
</tr>
</tbody>
</table>

Figures 4.1 and 4.2 show the cumulative frequency of hydraulic conductivity and sorptivity at USC during pre-burn, shortly post-burn and eight years after burn and the unburned watershed WGC during 2015. Within vegetation cover types, the greater values of K in USC at 2015 measurements are more frequent compared to pre-treatment condition, especially in Aspen. For comparison of vegetation type between USC and WGC in 2015, most of K values are very similar in Low Sage and Aspen, and frequency of K values of Big Sage in burned watershed is apparently different with that in unburned watershed-WGC. The frequency distribution curves for S in Low Sage and Big Sage at USC are similar for pre-treatment and post-treatment condition. The treatment conducted at Aspen shows a large difference between in the cumulative frequency curves of S, with a much greater frequency of negative S values in 2015 compared to pre-treatment in 2007.
The hydraulic conductivity varied along the transects (Figure 4.3). The range in K values and average K decrease with position downslope in Low Sage and Big Sage transects. The K values in USC and WGC Aspen transect are less spatially organized, but like the other transects show some increase in the average value upslope. Statistically, the
mean K values in the transect measured in 2015 were not significant different except the Big Sage transect of WGC which was significantly lower than other five mean values (table 4.3).

The S values at point scale were highly variable along each transect (Figure 4.3). In the Low Sage transect of USC and WGC, most S values were positive while the S values were negative in Big Sage and Aspen of USC and WGC. There is a general trend of S from positive to negative aligning with observed gradients in plant canopy cover, soil moisture and soil temperature.

The WRI values were highly variable along the transects (Figure 4.3). Most WRI values in Low Sage of USC and WGC were less than 60% (Figure 4.4). The WRI values range from 0-100% in the remaining transects at USC and WGC which indicates that infiltrability and the degree of water repellency distributed extremely uneven. From table 4.2, the average level of WRI for USC Big Sage and Aspen transect and WGC Aspen transect showed no significant differences. The average WRI of the Big Sage transect of WGC was significantly different than transects. Moreover, average values of WRI in Low Sage of USC and WGC, 19.92% and 19.72% respectively, were significantly lower than other transects.
Figure 4-3 Spatial distribution of hydraulic conductivity and sorptivity and WRI within Upper Sheep Creek (USC) and Wood Gulch Creek (WGC) watersheds, with study transects shown from northwest to southeast. Downslope direction indicates differences in drainage and direct solar radiation.
Table 4-2 Average hydraulic conductivity, water repellency index and organic fraction of carbon for all burned and unburned transects on USC and WGC watershed. Lower case letter within a column indicate significant (P<0.05) differences between transects.

<table>
<thead>
<tr>
<th></th>
<th>Hydraulic Conductivity cm/s</th>
<th>Water Repellency Index %</th>
<th>%C 0-5 cm</th>
<th>%C 5-10 cm</th>
<th>%C 10-15 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>USC-PreBurn (2007)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sage</td>
<td>0.47 b</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Big Sage</td>
<td>0.64 b</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aspen</td>
<td>0.66 b</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>USC-PostBurn (2009)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sage</td>
<td>1.29 a</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Big Sage</td>
<td>0.82 b</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>USC-AfterBurn (2015)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sage</td>
<td>1.3 a</td>
<td>19.92 c</td>
<td>3.2 b</td>
<td>1.8 b</td>
<td>1.43 c</td>
</tr>
<tr>
<td>Big Sage</td>
<td>1.62 a</td>
<td>57.13 a</td>
<td>10.11 a</td>
<td>4.73 b</td>
<td>3.13 b</td>
</tr>
<tr>
<td>Aspen</td>
<td>1.79 a</td>
<td>59.73 a</td>
<td>11.68 a</td>
<td>7.00 a</td>
<td>4.2 a</td>
</tr>
<tr>
<td><strong>WGC-Unburned (2015)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sage</td>
<td>1.45 a</td>
<td>19.72 c</td>
<td>2.51 b</td>
<td>1.54 c</td>
<td>1.29 c</td>
</tr>
<tr>
<td>Big Sage</td>
<td>0.9 b</td>
<td>42.17 b</td>
<td>11.04 a</td>
<td>6.14 a</td>
<td>4.15 a</td>
</tr>
<tr>
<td>Aspen</td>
<td>1.79 a</td>
<td>48.45 a</td>
<td>13.25 a</td>
<td>7.04 a</td>
<td>3.83 a</td>
</tr>
</tbody>
</table>
Individual values of Water Repellency Index for measurements from the 2015 infiltration study are compared as a dot chart representing each vegetation transect (Figure 4.4). As with the WDPT, the Low Sage transects showed the least intense WRI for water repellency, Big Sage showed the greatest difference in the distribution of values between USC and WGC.

![Figure 4-4 The values of water repellency index at each transect of USC (U) and WGC (W)](image)

The initial water content varied within and among vegetation dominated landscapes. In USC and the reference WGC watershed, the average initial water content was generally the least in Low Sage compared to other transects in the corresponding watershed. This
difference is attributed to canopy shading and topographic shading for Big Sage and Aspen, as shown by the mean initial temperatures of all transects (table 4.3). The Aspen transect had the greatest initial water moisture than others at the same watershed. Overall, the average initial water content was greater in WGC than that in USC for comparable vegetation transects due to a small rain event prior to soil water content measurement at WGC. Average final moisture content was remarkably similar within Low Sage transects (17%) and Big Sage transects (29%), but differed for Aspen. Whereas the average final moisture content for WGC (36%) was substantially greater than for Big Sage, final moisture content at USC Aspen was the same as Big Sage (Table 4.2).

Table 4-3 Average initial moisture content, $\theta_i$, standard deviation of $\theta_i$ and final moisture contents, $\theta_f$, the change in soil moisture content, $\Delta \theta$, Initial temperature $T_i$, final temperature $T_f$, and the change in soil temperature, $\Delta T$, for the 201 points of measurement in both USC and WGC transects

<table>
<thead>
<tr>
<th>Transect</th>
<th>$\theta_i$ (%)</th>
<th>STD ($\theta_i$)</th>
<th>$\theta_f$ (%)</th>
<th>$\Delta \theta$</th>
<th>$T_i$ (°C)</th>
<th>$T_f$ (°C)</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>USC_LS</td>
<td>4.4</td>
<td>1.8</td>
<td>17.0</td>
<td>12.6</td>
<td>31.5</td>
<td>31.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>WGC_LS</td>
<td>5.5</td>
<td>1.6</td>
<td>17.5</td>
<td>12.0</td>
<td>38.0</td>
<td>38.3</td>
<td>0.3</td>
</tr>
<tr>
<td>USC_BS</td>
<td>11.8</td>
<td>4.2</td>
<td>28.6</td>
<td>16.8</td>
<td>30.4</td>
<td>30.5</td>
<td>0.1</td>
</tr>
<tr>
<td>WGC_BS</td>
<td>20.8</td>
<td>6.6</td>
<td>28.8</td>
<td>8.0</td>
<td>23.4</td>
<td>27.6</td>
<td>4.3</td>
</tr>
<tr>
<td>USC_Aspen</td>
<td>14.0</td>
<td>5.2</td>
<td>28.9</td>
<td>14.9</td>
<td>23.8</td>
<td>20.7</td>
<td>-3.0</td>
</tr>
<tr>
<td>WGC_Aspen</td>
<td>25.9</td>
<td>7.3</td>
<td>36.1</td>
<td>10.2</td>
<td>26.5</td>
<td>26.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

An inverse linear relationship was found between Water Repellency Index (decreasing) as the Sorptivity (increasing) (Figure 4.5 and Figure 4.6). There is clear separation between Low Sage and Aspen, where most S values of Aspen are negative and most of Low Sage values are positive. S values for Big Sage are more numerous in the negative range but span nearly the entire range of all sites. Differences in vegetation cover, soil texture and distinct organic content (Table 4.2) may all contribute to the
differences in S. Based on regression line, sorptivity in those sites which have WRI lower than 40% tend to be positive. Since the parameters S and WRI were both calculated from the same time series infiltration data, the result may simply be autocorrelation between the factors controlling early time infiltration. The results indicate that there is inherent correlation between S and infiltration rate which is used to determine WRI.

Figure 4-5 Sorptivity of Low Sage and Aspen transects estimated from infiltration using Zhang (1997) compared to Water Repellency Index
4.2 Water Repellency

The WDPT test is a useful indicator of occurrence of SWR, though it may not be a conclusive method for determining the exact degree of repellency. Following the method, three classes of WPDT were used to assess the severity of water repellency at the mineral soil surface: 0-4s as wettable; 5-59s as slightly water repellent (Hydrophobicity I); and greater than 60s as strongly water repellent (Hydrophobicity II).

The occurrence of surface SWR by WDPT class and vegetation cover type are compared for measurements made at Upper Sheep Creek in 2007 and 2015 in order to identify any differences in post fire recovery at that site (Figure 4.7). Incidence of severely water repellent surface soils decreased for all cover types, but changes in wettable and
slightly water repellent soils varied among sites: In Low Sage, the frequency of wettable and slightly water repellent soils were similar, but the frequency of strongly water repellent soils decreased from 12% to 6% of the measured locations eight years after the fire. In the Big Sage area, where the fire was most severe, reductions in the frequency of wettable soil (-11%) and strongly water repellent soil (-13%) led to a relative increase in the fraction of slightly water repellent soil. The severity of SWR in Aspen decreased markedly after felling trees and manually burning the surface; the occurrence of strongly water repellent soil decreased from 72% to 22%. Slightly water repellent soils and wettable soils increased to 45% and 33% of the measured points, respectively.

Figure 4-7 WDPT for pre-burn (2007) and after-burn (2015) condition on USC

The WRI calculated from infiltration in the field was compared with average organic carbon of soil depth of 15 cm (Figure 4.8). The relation between WRI and organic carbon content is very weak suggesting that many other factors affect infiltration in the field.
Comparison of WDPT measured in the field and corresponding WRI calculated by infiltration rate for the 2015 Upper Sheep Creek survey shows no clear relationship between WDPT and WRI (Figure 4.9).

Figure 4-9 The WDPT and corresponding WRI of each point in USC in 2015
4.3 Organic Carbon and Nitrogen

Soil organic carbon and nitrogen measurements were compared first between methods and then between sites and transects to determine any influence of methodology, land cover or watershed treatment on observed differences. Measurements of SOC and nitrogen content were compared for 100 paired samples randomly selected from the collected soil cores to identify any difference between preparation 1 by grinding and drying at 78 Celsius, and preparation 2 by sieving and drying at 55 Celsius. The paired t test results in Table 4.4 show P values greater than 0.05 for %C (P=0.199) and %N (P=0.077), indicating that the null hypothesis cannot be rejected and two soil preparations do not cause a difference in the results of these analyses. Henceforth, results are presented for preparation 2.

Table 4-4 The results of paired t test

<table>
<thead>
<tr>
<th></th>
<th>%C</th>
<th></th>
<th>%N</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preparation 1</td>
<td>Preparation 2</td>
<td>Preparation 1</td>
<td>Preparation 2</td>
</tr>
<tr>
<td>Mean</td>
<td>3.14</td>
<td>3.25</td>
<td>0.26</td>
<td>0.28</td>
</tr>
<tr>
<td>Variance</td>
<td>4.20</td>
<td>5.92</td>
<td>0.025</td>
<td>0.029</td>
</tr>
<tr>
<td>Observations</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Pearson Correlation</td>
<td>0.94</td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>H₀</td>
<td>0</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>99</td>
<td></td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
<td>-1.29</td>
<td></td>
<td>-1.78</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.199</td>
<td></td>
<td>0.077</td>
<td></td>
</tr>
<tr>
<td>t Critical two-tail</td>
<td>1.98</td>
<td></td>
<td>1.98</td>
<td></td>
</tr>
</tbody>
</table>

Soil organic C and N varied substantially with cover type and depth and less between sites. The mean values of organic carbon ranged from (1.5 to 3.0 %) for the Low Sage
samples to (3.5 to 10%) for the Big Sage to (4.0 to 12.5%) for Aspen. Similar relative differences were found in the N samples, although the mass values are much less than for C (Figure 4.10). Mean values of both N and C are comparable for similar depths and cover class except for big sage (table 4.2), which was uniformly less at USC than WGC. The shift from similar average C and N content for shallow samples from aspen at USC and WGC to progressively lower values of C and N with depth for WGC is interesting and may be related to a difference in watershed treatment.
Figure 4-10 The average mass percent of soil organic carbon and nitrogen for sample depth of 0-5 cm, 5-10 cm and 10-15 cm for samples from Upper Sheep Creek (U) and Wood Gulch Creek (W) for the vegetation transects in low sagebrush (L), big sagebrush (B), and aspen (A). The associated error bars are calculated using 95% confidence interval. (n ≈10)

The scaled correspondence in the magnitude of C and N values by cover type (Fig. 4.11) results in relatively uniform C: N ratios between approximately 10:1 and 14:1, in agreement with the broad survey of elemental ratios in SOM by Kirkby et al. (2011). A
regular decrease in the C: N ratio with depth is exhibited for all soil classes, and the rate of decrease with depth for each cover class is greater for WGC transects than for USC, although the differences are not significant (Figure 4.10). The C: N ratio tends to slightly increase across Low Sage, Big Sage and Aspen.

Figure 4-11 The ratio of organic carbon to nitrogen at different depth of each transect from USC (U) and WGC (W) for Low Sage (L), Big Sage (B) and Aspen (A)

Approximately one quarter of the 163 soil samples collected from three depths across the six transects sampled in 2015 showed contact angles greater than 90 degrees. These samples were primarily from Aspen and High Sage transects and 75% of them were near the mineral soil surface (0-5cm). The contact angle measurement in this study showed the soil water repellency controlling of soil water content, soil structure and roughness of surface. The relation between SWR and contact angle for the water-repellent soils in this study is shown in Figure 4.12.
Figure 4-12 Relation between soil organic carbon and contact angle in water repellent soils
5 Chapter 5 Discussion

5.1 The Temporal Effects of Prescribed Burning on Soil Hydraulic Properties

Soil water repellency is a transient phenomenon at multiple spatial and temporal scales. This complicates evaluation of both the presence and associated hydrologic effects of SWR. For example, WDPT is often used to measure the level of persistence of water repellency in the field. This study found that WDPT measurements conducted in 2007 and 2015 in the USC grazing enclosure showed differences in persistence of water repellency (associated with the plant cover) from natural background to the condition eight years after fire. The different levels of SWR among transects for the pre-burn enclosure at USC and the occasionally grazed condition at WGC is clearly related to SOM content. However, the controls on the distribution of SWR within the transects are less clear. The study of Doerr (2009), which summarized various soil types, supported these findings that the soil water repellency can be a natural characteristic of soil.

The presence of strong water repellency was mitigated eight years after burning in both fire-treated Low Sage and Big Sage transects (Figure 4.7). Although the aspen area was not burned in 2007, the trees were felled. The presence and severity of SWR in the Aspen transect was significantly reduced after fire and felling compared to pre-fire condition. The results generally supported the hypothesis that the high severity of SWR after fire is alleviated over time in Big Sage and Aspen environments within the sagebrush ecosystem.
The cumulative frequency curves for hydraulic conductivity (Figure 4.1) showed that the cumulative frequency distribution in each transect changed little with burning, but greater change occurred across time with vegetation recovery from fire. In the Low Sage and Big Sage transects, the K values exhibited no significant differences (Table 4.2) between the pre-fire and shortly post-burn condition. However, the hydraulic conductivity tended to increase through time. Nearly 80% of the measured hydraulic conductivity values were less than $1 \times 10^{-3}$ cm/s before the fire and directly after fire in Low Sage, whereas only approximately 20% of measured K was less than this value eight years after fire (Figure 4.1). Similarly, at Big Sage and Aspen the means of K increased significantly (Table 4.2).

For sorptivity, the Zhang (1997) method produced both positive and negative values (Figure 4.3). The soil sorptivity is the capacity of unsaturated soil to absorb water by capillary pressure. In wettable soils, sorptivity is always positive and is a function of initial water content, hydraulic conductivity, porosity and air-entry tension for the Richards Equation. However, negative sorptivity which represents negative wetting front suction is theoretically possible for hydrophobic soils. The negative values of sorptivity were produced in this study due to second-term of second-order polynomial regression of cumulative infiltration. This can be explained that early infiltration rate for sites with negative sorptivity is relatively lower compared to late infiltration, which is near steady-state. This situation is the opposite of typical infiltration time series. The inhibited at early stage attribute to soil water repellency and therefore, SWR could be an explanation for negative sorptivity.

The cumulative frequency distribution of sorptivity for Low Sage was
approximately similar across the three periods of observation, including the aftermath of the prescribed fire (Figure 4.2), likely due to the great frequency positive sorptivity values. At the y axis intercept, approximately 17% difference was observed between 2015 and 2007 measurements in the Big Sage at USC, which indicates sorptivity increased 17% eight years after fire. This is in accord with the result of WDPT (Figure 4.8) that wettable soil decreased in 2015 compared to pre-burn condition at USC. Sorptivity in the aspen area in WGC was similar with that of USC at 2015 but rather significantly different with the aspen area of USC at pre-treatment condition. Therefore, there is no significant temporal effect of prescribed fire on sorptivity in Low Sage and Big Sage transect and but the effect of the treatment in the aspen is apparent for sorptivity through time.

In this study, the changes in infiltration and SWR indicate a better hydrological condition than the pre-burn condition in USC but changes are less significant among comparable vegetation covers between USC and WGC. The results of this study suggest that over relevant management time scales, SWR and hydrologic variables are more influenced by site vegetation rather than fire induced effects. This result is accord with previous studies which found that fire induced water repellency led to substantially reduction of saturated hydraulic conductivity (Fox, 2007) and infiltration rates (Martin, 2001), recovery over time to pre-burn conditions. Although many studies have documented the linkage between variations of soil water content and SWR (Dekker, 2001), relatively little is known about the other variables and process such as surface and subsurface hydrologic response that control the persistence of SWR after recovery (Doerr, 2006a).
5.2 Spatial variability of soil hydrological properties in small sagebrush watershed

Soil hydrological properties are unevenly distributed at the catchment scale. However, regular patterns can be observed based on plant cover within each catchment. Hydraulic conductivity (K) and the range in K in Low Sage and Big Sage transect of both USC and WGC (figure 4.3) decrease with distance down slope. No such ordination is apparent in the Aspen transect in USC and WGC. The hydraulic conductivity, K, depends on the soil texture, structure of the soil matrix and the type of fluid. Plant type and rooting behavior have been reported as a dominant role that affect soil structural porosity (Gregory, 2006; Pierret, 2011). Thus, soil texture associated with plant cover is assumed to be the controlling for spatial variability of hydraulic conductivity in the 2015 experiment. Also, explanation for down-slope pattern of hydraulic conductivity could be that hydraulic generally decreases along downslope under herbaceous cover, however, this pattern may not be observed in woody plants due to their powerful roots.

The spatial variability of sorptivity (S) is basically controlled by SOM and soil wettability. Spatially, S declines across the Low Sage, Big Sage and Aspen (Figure 4.3) and this trend corresponds to the general spatial distribution of average SOM through Low Sage, Big Sage and Aspen (Figure 4.9). Most positive S occurred in Low Sage and greatest negative S are present in Big Sage and Aspen. The presence of SWR also has similar performance in vegetation based transect (Figure 4.3 and Figure 4.8). This suggests that variance of sorptivity is related to the presence of SWR.

Plant communities play more important role in hydraulic parameters than landform in sagebrush ecosystems. As discussed above, hydraulic conductivity is basically
controlled by soil texture and plant cover. However, the hydraulic conductivity was significantly different in similar landform and plant cover (e.g. the Big Sage in USC and WGC). It is noted that USC is restricted for grazing but WGC is allowed to graze. The difference of this policy resulted in different biomass and organic matter input for USC and WGC. Thus, it could be explained for significant difference of K in the Big Sage between USC and WGC (Table 4.2). Moreover, the treatment conducted in the Aspen in USC led to substantial difference of hydraulic conductivity and sorptivity between measurements in 2007 and in 2015. Between landforms, hydraulic conductivity tended to decrease along downslope in the Low Sage and Big Sage but no such ordination in the Aspen. It is most likely based on the difference of root activity between herbaceous and woody plants.

Initial water content is primarily controlled by climate and soil texture. The initial water content associated with each plant cover in USC was lower than in WGC since a rain event occurred before the measurements were made on WGC. Initial water content in Low Sage of both USC and WGC was, however, distinctive compared to Big Sage and Aspen. Soil texture is primary reason for this difference, though different vegetation has various ability of water withholding. The soil profile in Low Sage is very shallow to basalt bedrock and thin surface loamy layer is mixed with silt. The soil in Low Sage has a low capacity for storing water. Therefore, the initial water content in USC Low Sage was similar to WGC Low Sage even though WGC Low Sage had been experienced recent rainfall.
5.3 The Relationship among Soil Organic Fraction, Soil Hydrophobicity and Infiltration Properties

The organic fraction of water repellent soil in these sagebrush ecosystems showed strong logarithmic relationship \( (R^2=0.66) \) with contact angle (Figure 4.12). The sessile drop method provides further insight into the relationship between water repellency and soil organic fraction in the laboratory while WDPT methods only can test surface persistence of water repellency. Other factors such as surface roughness (Philip, 1971) and chemical heterogeneity (Dettre, 1964) in the field are likely to complicate the relationship among these parameters. In this study, the contact angle measurement controlled for soil variables such as surface roughness, soil moisture and soil temperature. Two black dots from the Low Sage in Figure 4.11 are exceptional because others data are condensed around regression line. It is noted that there were substantial numbers of soils with contact angle smaller than 90° that SOC between 3.5% and 5.45% (last third dot). For sandy loam in sagebrush ecosystem, the values of soil organic carbon which are greater than 3.5% will tend to increase in hydrophobicity by increasing the tension at liquid and solid interface. It is safely concluded that for those soils whose organic carbon greater than 5.45% are most likely to be water repellent.

The positive relation between SWR and SOM has often been reported. Orzechowski (2013) qualitatively concluded that the presence of SWR is more frequent in soils with greater organic matter by testing soils with various organic content. In the study of Jiménez - Morillo (2014), a positive exponential relationship between SOM and \( \log(\text{WDPT}) \) was observed but SOM was not the dominant factor as soil sieve fraction exerts different SWR values in similar content of SOM. He explained that this
difference may due to lower degree of evolution of SOM with higher content of fatty acids and alkane/alkene.

The WRI showed a weak positive relationship with the average SOC in soil samples within 15 cm of the surface (Figure 4.8). This weakness of this relationship is likely factors other than SOC that strongly influence WRI. For example, infiltration in the field can be affected by other soil properties such as particle size distribution, soil horizonation, barriers to flow such as stone fragments, roots and biogenic voids, and soil moisture. These factors in each transect are not homogenous. Moreover, since WRI reflects the difference in position of the wetting front between the initial and final infiltration, WRI is influenced by anisotropy in soils.

The relationship among water repellency and hydraulic parameters such as K, S, WPDT and WRI were investigated. No trends or significant relationships among SWR K, and SWR and S where SWR is determined by WDPT were observed. However, general linear correlation was observed between WRI and S (Figure 4.5 and Figure 4.6). The clear separation of positive and negative S values across Low Sage Big Sage and Aspen by the differences in soil moisture, biomass and associated SOC across the watersheds. which lead to negative S. The result indicates that S has an inherent correlation with SWR phenomenon.

The ratio of carbon to nitrogen has significant effects on decomposition (Enriquez, 1993) and is correlated to immobilization and mineralization of nitrogen (Janssen, 1996). Low C/N ratio is often indicative of high rates of N mineralization and rapid rate of decomposition. Relatively high C/N ratio indicates N immobilization and slower decomposition rate. The average values of organic carbon and nitrogen were distinct
between the Low Sage transect and the other transects (Figure 4.11). The average organic C and N of USC transects were not significantly different from the comparable WGC transects (Table 4.2). The ratio of C/N decreased with depth in the soil profile with little difference between similar transects. This suggests that despite large differences in C and N concentrations, between vegetation community, decomposition and nutrient cycling processes of SOC are controlled by availability of soil nitrogen.
6 Chapter 6-Conclusion

The objective of this study was to understand the long-term effect of prescribed burning on soil hydrologic properties in sagebrush-steppe ecosystems. To accomplish this goal, field measurements of infiltration were made, WDPT tests were conducted in-situ, soil cores were extracted and contact angle measurements were made. The infiltration measurements were analyzed to determine hydraulic conductivity, sorptivity and water repellency index. Subsamples of soil cores were analyzed for soil organic carbon and nitrogen and used to measure soil-water-air contact angle was subjected to investigate the relationship between soil water repellency and soil organic matter content.

The comparison of WDPT found that the severity and presence of surface soil water repellency was reduced eight years after treatment in the sagebrush-steppe ecosystem of Upper Sheep Creek. Not only did the prescribed burning on Low Sagebrush and Big Sage in USC result in decreased incidence and strength of water repellent soil, but also the physical removal of the over story canopy Aspen also resulted in a reduction in the severity of water repellency. When comparing the infiltrability and water repellency between the burned watershed of USC and unburned watershed of WGC using WRI, there were no significant differences between the homogenous landscapes of these two watersheds.

It was found that hydraulic conductivity in each transect in USC significantly increased over the period from before the burn to eight years after treatment. Fire or other treatment may have changed input of organic matter (e.g. from Woody plants to
grasses) and influence the biochemical process of microbes in the soil which affect soil properties. Spatial variability in hydraulic conductivity is assumed to be controlled by soil texture and plant cover. When comparing hydraulic conductivity and WDPT and WRI respectively, it was found that hydraulic conductivity is not directly related to soil hydrophobicity in rangeland settings.

Sorptivity was inversely related to WRI and negative sorptivity is related to SWR. Sorptivity in USC in three sampling periods from before the burn to eight years after treatment in Aspen sites was significantly different but were not at Low Sage and Big Sage. The percentage of positive sorptivity measurements in pre-burn condition at aspen is greater than after-burn condition. This result is not consistent with the result of WDPT, which suggests that the occurrence of wettable soil increased in after-burn condition at aspen. The possible explanation is that WDPT measurement is not well representative for the SWR of the soil profile.

My results have implications for rangeland managers regarding the long-term effects of prescribed fire treatment on soil hydrologic properties. Prescribed fire is applicable for grazing in semiarid rangeland, as palatable vegetation for livestock and soil hydrologic properties will recover to previous conditions or even better after fire, though it also will lead to high variance of hydrological properties.

A limitation of this research was the lack of WPDT data from shortly after burning. Increased water repellency may be a result from fires, but the eight-year time break complicates the interpretation for short-term effects of fire and hydrologic recovery. Further research would be beneficial to assess more site factors such as maximum site temperature, site slope with soil water repellency and water balance. It also would be
helpful to conduct more laboratory experiments with controlled conditions compared
with field measurement because the results from in-situ measurements showed a
complicated picture of SWR in the soils. Finally, the results obtained from one study
site may be not applicable for other sites, so the results of this study may be limited to
silt loam soils of sagebrush steppe ecosystems.


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Pierson, F. B., Robichaud, P. R., & Spaeth, K. E. (2001). Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological...*


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(doi:10.1080/00103624.2015.1081927)


**HONORS**

2012 Third Prize, Elite College Researcher, Hubei Province
2012 HZAU Activists of Scientific and Technical innovation
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