CHARACTERIZING THE EVOLUTION OF FIRE INDUCED HYDROPHOBICITY IN THE POST-FIRE ENVIRONMENT AND EVALUATION OF ASH AND CHAR AS POTENTIAL SOURCES OF HYDROPHOBICITY

A Dissertation

by

NATHAN THOMAS GARDINER

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Chair of Committee,	Bruce E. Herbert
Committee Members,	Kevin McInnes
	Thomas McDonald
	Eric Riggs
	Michael Pope
Head of Department,	Michael Pope

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ABSTRACT

Managing fire-induced water-repellent soils in the aftermath of a severe fire can be troublesome and challenging. The water-repellent layer decreases the soil permeability and prevents moisture from entering the soil profile. In the post-fire environment uneven moisture distribution can hinder germination and revegetation. In addition, the decreased permeability caused by the water-repellent layer leads to increased runoff and soil erosion. Erosion robs the soil of its ability to support vegetation, and can lead to increased gully and rill formations, channel erosion, and slope failure. This study documents the evolution and explores the mechanisms of formation of soil water repellency created by the Lost Pines fire near Bastrop, TX. It also examines the potential role of ash and char created by the fire, in altering soil hydrology, and examines management implications.

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Contributors

This work was supervised by a dissertation committee consisting of Dr Bruce Herbert (Advisor), and Dr Michael Pope, Dr Eric Riggs, Dr Kevin McInnes, and Dr Thomas McDonald.

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1. INTRODUCTION

Forest fires are typically viewed as unique, one-time catastrophic events. The management of forest resources after a fire represents a complex environmental and ecological management issue (Fischer and Binkley 2000). One of the major problems to address in post-fire forests is soil erosion. The increased soil erosion following a wildfire is most often attributed primarily to the loss of vegetative cover. However, fire also alters the properties of the soil itself. One of the possible changes to fire-affected soils is the potential for the creation of a water repellent, i.e., hydrophobic, layer near the soil surface. A water-repellent soil layer is simply a layer that slows or resists water infiltration into the soil. Fire-induced water repellency is highly correlated to fire intensity and is thought to form primarily through the volatilization and subsequent re-condensation of hydrophobic compounds typically found in leaf litter. The principle effect of soil water repellency (SWR) on the hydrologic cycle is reduced infiltration into the water-repellent soils. This results in an increased probability of overland flow. As the depth and velocity of the overland flow increases, the potential for erosion and sediment transport also increases (Meeuwig 1970, Doerr, Shakesby et al. 2009). Increased overland flow can result in increased rill erosion, gully formation, bank and channel erosion, and mass wasting along steep hillslopes (Moody and Martin 2001).

Establishing a direct correlation between soil water repellency and runoff is complicated by the loss of the protective leaf layer, the reduction of interception due to the canopy loss, structural changes in the soil itself, and the loss of soil organic matter

(Shakesby, Coelho et al. 1993, Moody and Martin 2001, Doerr, Shakesby et al. 2009). Because soil water repellency is generally related to fire severity, it can be highly variable across a landscape. Therefore, any impact soil water repellency may have on runoff and soil erosion will also be highly variable across the landscape. These factors make predicting the effects of soil water repellency and predicting soil erosion in the post-fire environment very sensitive to scale. The transient nature of the water repellency only compounds the difficultly of predicting soil erosion after a catastrophic fire and the development of effective forest management techniques.

1.1. Nature of Fire-Induced Water Repellency

Soil water repellency was first recognized by scientists and land managers well over a century ago, but the first published accounts of fire-induced water repellency appear in the 1960s (DeBano 2000). In general soil water repellency reduces the affinity of soils to water such that they resist wetting (King 1981, Doerr, Shakesby et al. 2000, Doerr and Thomas 2000). Because soils can be water repellent for a variety of reasons, soils that have become water repellent as the result of wildfire are a unique subset of water-repellent soils.

At one time soil water repellency was considered an uncommon phenomenon limited to a handful of unique environments, but over the years naturally occurring SWR has been reported in a wide variety of environments and soil types. It has become a common management concern in pine forests, eucalyptus forests, and on agricultural lands and golf courses. It has become clear that water repellent soils are quite common and distributed worldwide.

Molecules with hydrophobic properties are abundant in the environment. Plants produce hydrophobic compounds to minimizes desiccation, and protest themselves from insects, and microbes. These molecules are relatively persistent in the natural environment, common in vegetated soils, and are believed to be the primary source of soil water repellency (Doerr, Shakesby et al. 2000, Doerr, Shakesby et al. 2009).

Creation of the water repellent layer was described as a “tin roof” effect by earlier watershed researchers (DeBano 2000). After a wildfire, soil is typically covered by ash and char overlaying a layer of burned soil. If present, a water-repellent layer is typically found as a discrete layer beneath the ash and burnt soil, at or near the mineral surface. The water-repellent layer typically runs parallel to the soil surface, and can be of variable thickness and spatial continuity (DeBano 2000).

Despite the potential for other mechanism current research into fire-induced SWR focuses almost exclusively on only one mechanism of formation. The water repellant layer is generally thought to be produced through the combustion of leaf litter which leads to the volatilization and re-condensation of hydrophobic compounds found in leaf litter. The heat produced during a wildfire creates large temperature differences between the surface layers of the mineral soil. During a fire, temperatures in a burning canopy can reach over 1100°C, and temperatures at the soil-litter interface can reach 850°C (Countryman 1964, DeBano 2000). But temperatures at a depth of 5 cm beneath the soil surface rarely exceed 150°C because soil is such an effective insulator (DeBano

2000). Heat generated by the combustion of the litter layer at the soil surface vaporizes organic substances found in the leaf litter. The heat produces a steep vertical temperature gradient in the surface layers of the mineral soil. The steep temperature gradient pushes the volatilized organic compounds toward the cooler underlying soil layers, where they condense onto the surface of soil particles creating a water-repellent coating around the particle (DeBano 2000, Letey 2001). The heat from the combustion of the litter is also thought to cause conformational changes which may make these compounds more hydrophobic (Doerr, Douglas et al. 2005). Burning also is thought to facilitate the bonding of the hydrophobic substances to the soil particles (Savage, Osborn et al. 1972).

The result is a water-repellent layer running approximately parallel to the soil surface of the burned area. The movement of hydrophobic substances down into the soil profile occurs primarily during the fire but may continue for a greater duration because the soil may stay warm for several days following a fire. If the heat from a wildfire lingers for several days it can re-volatilize some of the hydrophobic substances leading to a strengthening of water-repellent layer (Savage 1974).

Research on fire-induced water repellency has not revealed a specific compound of set of compounds responsible for fire induced water repellency hydrophobic substances, nor have the specific conformational changes occurring to these compounds been determined (DeBano 2000). Given the infinite number of organic compounds potentially present in the leaf litter and soil, and the complex chemistry of these compounds during heating, the failure to identify a specific set of compounds is not surprising (DeBano 2000, Doerr, Dekker et al. 2002).

1.2. Fire Severity

Many variables contribute to the formation of a water repellant layer; but simply stated, water repellent layers are most likely to form in severely burnt areas (DeBano and Krammes 1966, DeBano 1966, DeBano, Mann et al. 1970, Savage 1974, DeBano, Savage et al. 1976). Laboratory studies have repeated shown that very little change in water repellency occurs below 175°C. Between 175°C and 200°C water repellency begins to develop and eventually peaks between 250 and 280°C. Above 280°C destruction of the hydrophobic properties begins and continues as temperatures reach about 400°C (DeBano 1981, DeBano 2000). This temperature dependency may explain observations that intense fire destroys water repellency in some soils with naturally occurring water repellency. Fires can also serve to intensify pre-existing water repellant or cause the hydrophobic layer to shift deeper into the soil profile.

1.3. Soil texture and organic matter

Because of the lower particle surface area course-textured soils are more susceptible to the development of soil water repellency than finer textured soils. This lower surface area provides fewer potential adsorption sites for hydrophobic organic molecules (Doerr, Shakesby et al. 2009).

Some soil and vegetation combinations are much more likely to produce strong water repellency. Vegetation that produces large amount of oil or wax covered leaves such as sclerophyllous shrubs, conifers, and eucalypts, are more likely to induce soil water repellency (Doerr, Shakesby et al. 2000, Doerr, Shakesby et al. 2009).

However, it is still not completely clear why some soils exhibit water repellency and others do not; and, it is not currently possible to accurately predict the strength of soil water repellency based on the type or quantity of organic matter present in the pre-fire environment (Doerr, Douglas et al. 2005, Doerr, Shakesby et al. 2009).

1.4. Variability in time and space

In the weeks and months after a fire, soil hydrophobicity can vary greatly over time and space. Much of the temporal and spatial variability in hydrophobicity relates to spatial and temporal variability in soil moisture content—which is itself affected by the extent and intensity of the soil's hydrophobicity. Hydrophobicity can change rapidly in response to changes in soil moisture. A water repellent soil may resist wetting for long periods, but water will eventually enter the soil (Doerr, Shakesby et al. 2009). A soil moisture threshold exists at which the soil shifts from being water repellent to being readily-wettable (Dekker, Doerr et al. 2001, Doerr, Shakesby et al. 2009). Reported critical thresholds range from as low as 5 percent (by volume) in dune sands, to as high as 30 percent for finer textured soils (Dekker, Doerr et al. 2001, Doerr, Shakesby et al. 2009).

As a previously water-repellent soil dries out, the repellency may or may not return. The return can be gradual or immediate. Water repellency tends to be weaker upon re-establishment, but data on this is scarce (Doerr, Shakesby et al. 2009). The exact processes involved are not fully understood, but a few studies have proposed that water returning to the soil after a fire induces conformation changes in the hydrophobic substances, which are retained even after the soil dries out (Roy and McGill 2000, Morley, Mainwaring et al. 2005).

The longevity of fire-induced water repellency depends on some of the same factors that affect its formation. The longevity of fire induced water repellency can be highly variable, and relatively little is known about the processes that control post-fire SWR as functions of time (DeBano 2000, Doerr, Shakesby et al. 2009). Research in this area is hindered by the difficulty in distinguishing long term changes in water repellency from the natural variability in measurable water repellency associated with shifting soil moisture levels (Doerr, Shakesby et al. 2009).

1.5. Quantifying soil water repellency

A water-repellent soil is classified as one on which a drop of water will not spontaneously penetrate. The default method for quantifying soil water repellency has long been the Water Drop Penetration Time (WDPT) test. In this method, a drop of water is placed on the soil surface and the time required for the water to penetrate the soil surface is recorded. In most cases the drop will eventually penetrate the soil in a time period that differs among soils. The larger the value of WDPT, i.e., the greater the time needed for the drop to penetrate, the greater the extent of repellency (Letey 2001). Values greater than 18 seconds are generally considered to indicate strongly water repellent soils, while values of greater than 90 seconds indicate extreme water repellency (Doerr, Shakesby et al. 2009).

A water drop that does not immediately penetrate indicates that the water–soil contact angle is equal to or greater than 90°. Over time that soil surface changes so that the contact angle shifts from being greater than 90°C to being less than 90°, and the drop penetrates the soil. In this way, the WDPT characterizes the stability or persistence of the water repellency, rather than its strength (Letey 2001).

The other common method for quantifying water repellency is the Molarity of Ethanol Droplet (MED) test. The MED test uses the known surface tensions of standardized solutions of ethanol in water. In performing the test, drops of ethanol in water solutions of increasing concentration are applied to the soil surface. A droplet with a higher surface tension than that of the soil surface will remain on the soil surface for some extended period of time; whereas, a droplet with a greater concentration of ethanol, and therefore having a lower surface tension, will infiltrate more rapidly if not instantly. Drops with decreasing surface tensions (increasing ethanol concentrations) are applied until a drop infiltrates into the soil. If small enough increments are used, the surface tension at the time of infiltration contact can be determined accurately (Letey, Carrillo et al. 2000, Letey 2001). Where the WDPT measures the persistence of the water repellency, the MED measures the strength or severity of water repellency (Letey, Carrillo et al. 2000, Letey 2001).

Table 1-1 Ethanol concentrations, Molarity of an Ethanol Droplet (MED), apparent surface tension (γ) and associated descriptive classifications (Doerr 1998, Doerr, Shakesby et al. 2009).

% Ethanol (vol.)	Molarity (MED)	γ (mNm^{-1})	Severity Rating
0	0	72	none
1	0.2	67	
3	0.5	61	
5	0.9	57	slight
8.5	1.5	51	moderate
13	2.2	46	strong
18	3.1	42	very strong
24	4.1	39	
36	6.1	33	extreme

By measuring the stability of the water repellency, the WDPT is perhaps more useful with regards to predicting the effects of the water repellency on hydrologic processes. However, the MED is a much quicker test. The long sample times associated with the WDPT, often lasting several hours, make the test impractical for large scale field work. Because the persistence of water repellency and the strength thereof are somewhat independent, correlating the two properties is of little value. The persistence of the water repellency is often related to the severity, but the relationship is not always clear or consistent (Doerr, Shakesby et al. 2009). In general, but not always, MED values correspond reasonably well to WDPT values for highly water repellent soil, but not as well for moderately or slightly water repellent soils (Letey, Carrillo et al. 2000, Letey 2001).

In recent years, a Mini-disk infiltrometer has been used to measure infiltration into soil after fires. The instrument is a field portable porous disk device used to quickly measure the unsaturated hydraulic conductivity of the soil. The instrument allows for adjusting the level of suction required in order to appropriately assess the hydraulic conductivity of soils of various texture (Robichaud, Lewis et al. 2008).

The primary methods for evaluating the water-repellent layer are phenomenological, meaning that they study the effects of the layer, rather than the layer itself. This makes comparing data from different sites difficult. In addition, the WDPT, and to a lesser extend the MED, are dependent upon soil moisture levels. There is a need to develop a better way to quantify the water-repellent layer that is neither method dependent nor effected by soil moisture levels.

1.6. Incorporation of ash and char as another potential mechanisms of fire induced soil water repellency

The complex and often non-linear evolution of soil water repellency in the months following a wildfire hint at the potential for other mechanisms to contribute to the observed SWR. Ash and char do not contribute to the formation of water-repellent layer during a fire, but as they become incorporated into the soil over time, may produce significant ecological, hydrological and geomorphological effects. Ash is part of several biogeochemical cycles, including the carbon (C) cycle (Bodí, Martin et al. 2014). Ash and char modified soil infiltration and can also alter runoff and erosion rates (Woods and Balfour 2010, Bodí, Doerr et al. 2012). Ash and char can be incorporated into the soil, modifying physical and chemical soil properties which influence soil microbes and plant germination and growth (Raison 1979).

Within the fire research community the term ash encompasses the entire spectrum of residue produced by the combustion of vegetation (wood, roots, leaves, leaf litter, duff, etc.) during a fire (Goforth, Graham et al. 2005, Cerdà and Doerr 2008, Woods and Balfour 2008, Balfour and Woods 2013, Bodí, Martin et al. 2014). After a fire ash blankets the landscape, and the depth and continuity of ash is known to vary spatially within a burn area. The thickness of the ash layer is primarily a function of the pre-fire fuel load (Lavee, Kutiel et al. 1995, De Luis, González-Hidalgo et al. 2003, Cerdà and Doerr 2008, Woods and Balfour 2008, Balfour and Woods 2013). The physical and chemical properties of the ash are largely dependent upon fire temperature (Bodí, Mataix-Solera et al. 2011, Bodí, Martin et al. 2014).

Ash produced temperature below 250°C consists primarily of low-density charred particles with a density of less than $1 g/cm^3$ (Mulleneers, Koopal et al. 1999, Rumpel, Alexis et al. 2006). The loss of mass progresses at different rates depending on the plant species; but at these lower fire temperatures, as much as 60% of the loss can be due to volatilization of water (Mutch and Philpot 1970, Dimitrakopoulos and Panov 2001, Úbeda, Pereira et al. 2009, White and Zipperer 2010).

Between 250°C and 300°C aromatic compounds begin to form in the char as hydrogen begins to volatilize (Kuo, Herbert et al. 2008). Ash created at temperatures below 350°C can be either hydrophobic or hydrophilic. The water repellent behavior is a product of aromatic, aliphatic, and carboxylic compounds, and is generally regarded as being a function of the ratio of organic carbon content to carbonates (Dlapa, Bodí et al. 2013). As temperature increases from 350°C to 450°C, oxidation is more intense, organic matter content declines, and the ash becomes hydrophilic, and lighter in color (Quill, Angove et al. 2010, Hogue and Inglett 2012, Balfour and Woods 2013). Above 500°C, organic compounds are almost completely combusted, leaving a light gray or white colored-ash composed primarily of silica and carbonates (Ulery and Graham 1993, Goforth, Graham et al. 2005). Ash produced at temperatures above 900°C contained mainly silica and oxides(Bodí, Martin et al. 2014).

Severe fires can result in complete combustion of the organic material generating carbon dioxide (CO2), carbon monoxide (CO), methane (CH4) or nitrogen dioxide (NO2), leaving only mineral ash. However, wildland fires typically burn under a mosaic of conditions, producing a mixture of pyrogenic black carbon, and mineral ash (Goldberg 1985, Schmidt and Noack 2000, Ormeno, Cespedes et al. 2009, Saura-Mas, Shipley et al. 2009).

Ash can become incorporated into the soil profile potentially modifying soil hydraulic properties. Ash incorporation has sometimes been shown to increase water retention (Stoof, Wesseling et al. 2010), but ash has also been reported to clog soil pores and reduce infiltration rates (Woods, Birkas et al. 2007, Woods and Balfour 2008). The effects of incorporation of water-repellent char into soil has not been fully explored, and it seems plausible that the water repellant char may induce water repellent behavior in the soil. Furthermore, because the aromatic compounds are recalcitrant in the environment, persisting for decades, this induced water repellency may also persist in the soil.

1.7. Research Objectives

My research emerged as a project of opportunity because of the Lost Pines fire that devastated Bastrop State Park. The initial experiments that I conducted sought to determine the potential ecological consequences of the Lost Pines fire, (i.e. increase erosion, impaired revegetation) and potential management implications for fire-induced soil water repellency. My central research question emerged from these initial experiments.

The central hypothesis of my research is that specific environmental factors, such as soil properties, slope and vegetation prior to the fire, controlled the nature and spatiotemporal evolution of soil water repellency in fire-affected soils after the Lost Pines Fire. Specifically, my research objectives were to (1) investigate the soil and landscape properties effecting the formation and longevity of fire-induced soil water in the post-fire environment, (2) characterize the influence of ash and char on soil water repellency and to induce significant changes in soil hydraulic properties, and (3) characterize management implications for fire-induced soil water repellency.

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2. FORMATION AND EVOLUTION OF SOIL WATER REPELLENCY FOLLOWING THE LOST PINES FIRE, BASTROP TEXAS

2.1. Introduction

Managing fire-induced water-repellent soils in the aftermath of a severe fire can be troublesome and challenging. The formation of a water-repellent layer in fire-affected soils has been referred to as the “tin roof effect” (DeBano 2000) The water-repellent layer decreases the soil permeability and prevents moisture from entering the soil profile. In the post-fire environment uneven moisture distribution can hinder germination and revegetation (Madsen, Petersen et al. 2012). In addition, the decreased permeability caused by the water-repellent layer leads to increased runoff and soil erosion. Erosion robs the soil of its ability to support vegetation, and can lead to increased gully and rill formations, channel erosion, and slope failure (Meeuwig 1970, Moody and Martin 2001, Doerr, Shakesby et al. 2009, Moody, Kinner et al. 2009, LPRT 2011).

Fire-induced water repellency is highly correlated to fire intensity and is thought to form primarily through the volatilization and subsequent re-condensation of hydrophobic compounds typically found in leaf litter. Many variables contribute to the formation of a water repellant layer, but water repellent layers are most likely to form in severely burnt areas (DeBano and Krammes 1966, DeBano 1966, DeBano, Mann et al. 1970, Savage 1974, DeBano, Savage et al. 1976). If present, a hydrophobic layer is typically found as a discrete layer beneath the ash and burnt soil, at or near the mineral surface. The hydrophobic layer typically runs parallel to the soil surface, and can be of variable thickness and spatial continuity (DeBano 2000). Coarse-textured soils are more susceptible to the development of soil water repellency than finer textured soils (Doerr, Shakesby et al. 2009). Some soil and vegetation combinations are much more likely to produce strong water repellency (Doerr, Shakesby et al. 2000, Doerr, Shakesby et al. 2009).

The volatilization and condensation of hydrophobic compounds onto the surface of soil grains is not sufficient to explain the complex behavior of water repellency in the weeks and months following a wildfire. It is still not completely clear why some soils exhibit water repellency and others do not ; and, it is not currently possible to accurately predict the strength of soil water repellency based on the type or quantity of organic matter present in the pre-fire environment (Doerr, Douglas et al. 2005, Doerr, Shakesby et al. 2009). A water repellent soil may resist wetting for long periods, but water will eventually enter the soil (Doerr, Shakesby et al. 2009). As a previously water-repellent soil dries out, the repellency may or may not return. The return can be gradual or immediate.

In the weeks and months after a fire, soil water repellency can vary greatly over time and space. This paper seeks to integrate post-fire field observations with laboratory experiments in order better understand the factors contributing to the formation of water-repellent soils. The chief hypothesis of this project is that specific environmental factors, such as soil properties, vegetation prior to the fire, and fire intensity control the nature and spatiotemporal evolution of soil water repellency in fire-affected soils after the Lost Pines Fire. Specifically, my research objectives were to (1) investigate the environmental properties that affected evolution and formation SWR, (2) characterize the relationship between measured soil water repellency and infiltration, and (3) determine which of plant species present at the study site contribute to the formation of soil water repellency.

2.2. Material and Methods

2.2.1. Study Location – The Lost Pines

The Lost Pines Forest is a unique 13-mile belt of loblolly pines (*Pinus taeda*) in Bastrop County, Texas. This small isolated belt of pine tree is separated by more than 100 miles from Piney Woods region that covers parts of Texas, Arkansas, Louisiana, and Oklahoma. The Lost Pines is thought to be the remnant of a much larger pine forest that shrank in size during the last glacial period of the Pleistocene era (Al-Rabab'ah and Williams 2004). In addition to the loblolly pine the primary species in Lost Pines Forest are Black Jack Oak (*Quercus marilandica*), Eastern Red Cedar (*Juniperus virginiana*), and Yaupon Holly (*Ilex vomitoria*).

2.2.1.1. Lost Pines Fire

The Lost Pines fire was a major wildfire of historic proportions that struck Bastrop County, Texas, in September and October 2011. Three separate fires started on September 4, 2011, and merged into one large fire that moved south in a progressively widening wedge. The fire occurred following a year of extreme drought. The area had not received significant rainfall in over a year prior to the fire. Strong winds from tropical storm Lee may have contributed to the rapid spread and difficulty fighting the fire. A total of 33,418 acres were burned(LPRT 2011).

Most studies done in the United States involving fire-induced water repellency are from the western half of the country, particularly the states of California, Oregon, Colorado, and New Mexico. Very few studies have identified fire-induced water repellency east of the Rocky Mountains. The Bastrop fire presented an opportunity to study the formation and evolution of soil water repellency in a unique setting. A series of study plots were established on a property within the burn zone. The property is located, immediately north of the intersection of Park Road 1C and Cottletown road. Fire burned through the area on September 5th and the property contains patches of various fire severities. A steep ravine bisects the property. The area west of the ravine was severely burned while the area east of the ravine is a mix of severe, moderate, and lightly burned patches. Prior to the fire the area was covered with mixed forest.

2.2.2. Field Assessment of Soil Water Repellency

On the selected property, twelve, 4-meter by 4-meter plots were laid out. Nine of the 12 plots were placed in heavily burned areas with three plots each on a small hilltop, next to the ravine, and at the bottom of the ravine. Two plots were placed in lightly burned areas, and one was placed in a moderately burned area. Fire intensity was determined using USDA guidelines (Parsons, Robichaud et al. 2010).

Water repellency was measured within the plots using the MED methodology (Lewis, Wu et al. 2005, Woods, Birkas et al. 2007, Balfour 2015). Water repellency was measured at the meter nodes so that 25 measurements were taken per plot. All initial water repellency data was collected within 21 days of the fire before the area received any post-fire precipitation.

In addition, the water repellency measurements, soil was also collected at the meter nodes. Where possible the top 10 cm of soil was collected and stored in plastic bags. In some cases, it was not possible to collect soil samples. The plots at the bottom of the ravine were largely too rocky to collect samples, and in a handful of other instances the sample nodes fell on rocks, holes, burned out tree trunks, etc. The soil samples were later analyzed for soil texture and soil organic matter. Textural analysis was done using a standard soil hydrometer methodology (Gregorich and Carter 2007). Soil organic matter was determined with a laboratory furnace using a standard loss of ignition (LOI) methodology (Gregorich and Carter 2007).

Using the same methodology, soil water repellency of the plots was measured the following March, May, June, July, August and September. By September 2012, only minimal soil water repellency existed at the study site, and subsequent attempts to identify soil water repellency at the site in March of 2013 and June of 2013, showed no further repellency.

In addition to measuring soil water repellency, unsaturated hydraulic conductivity was also measured within the plots during June, July and August using a mini-disk infiltrometer set at -2.0 cm of suction. (Decagon Devices, Inc.)

2.2.3. Laboratory Based Research

After the initial collection of field data collected immediately following the fire, a series of laboratory studies was conducted to isolate and quantify the contribution of the various environmental parameters to the measured SWR.

Vegetation and soil collected from the Bastrop area were heated in a laboratory furnace at various temperatures to induce water repellency. Two soils found at the field study site were chosen for laboratory experiments. The first soil is Robco loamy fine sand (loamy, siliceous, active, thermic Aquic Arenic Paleustalf) which covers most of the field site. The second soil selected is Rosanky fine sandy loam (fine, mixed, semi-active, thermic Ultic Paleustalf). The Rosanky soil is located on the north slope of a hill and is the highest point of the field site. The soils were collected from unburned areas near the field site and transported to the laboratory and air dried.

Four plant species were chosen for laboratory experiments. These plants are the four-dominant species of the forests of Lost Pines area at or near climax succession. The species chosen are loblolly pine (*Pinus taeda*), yaupon holly (*Ilex vomitoria*), eastern red cedar (*Juniperus virginiana*), and the post oak (*Quercus stellata*). Leaf or needle samples were collected from mature trees near the field site. The collected samples were oven dried at 70°C.

The soil was air died and then placed in a series of small steel cans. Two hundred grams of soil was placed into each can. Either 2g or 4g of one type of leaf sample was placed onto the soil surface inside the can. The cans, with soil and leaf tissue were placed into a muffle furnace for 60 minutes at one of either 200°C, 240°C, 280°C, 320°C, or 360°C. Four replicates of each soil/leaf/temperature combination, including controls with no added leaf tissue, were prepared and heated.

Following heating, the cans were left to cool overnight. After the cans had cooled, the remaining vegetation was removed using forceps, and the relative water repellency was measured using the MED methodology. In this process drops of weak ethanol solutions of increasing concentration are dropped onto the soil surface. The relative water repellency is determined by observing and recording the drop with the greatest concentration of ethanol which remains perched atop the soil surface for at least 5 seconds. Following the determination of relative water repellency unsaturated hydraulic conductivity of the soil in each can was measured using a mini-disk infiltrometer (Decagon Devices). Measurements were taken at 10-second intervals for the first 60 seconds. After the first 60 seconds, measurements were taken at 60 second intervals until 15 minutes had elapsed or infiltration ceased.

2.3. Results and Discussion:

2.3.1. Temperature Dependence of SWR

A summary of the data collected in the initial field survey is present in Table 2-1. All 12 field plots exhibited some SWR after the fire (Figure 2-1). A Kurskal-Wallis test on the initial (September 2011) soil water repellency measurements indicated that significant differences existed amongst the plots (p-value < 0.001) (Addinsoft, 2019). Pair-wise comparisons showed the data grouped in six different overlapping clusters with the lightly burned Plots 5 and 6 at one extreme and the Rosanky heavily burned plots at the other (Table 2-2), indicating that the measured soil water repellency (SWR) was weakly correlated with the field-determined fire intensity, and that at least for the heavily burned areas the Rosanky soils exhibited greater soil water repellency.

For the laboratory data the correlation between temperature and SWR was even stronger. In the laboratory, water repellency begins forming at 200°C and peaks at 280°C. By 360°C the water repellency is gone in both soils. In general, the Robco soil showed a greater response than the Rosanky soil, which was the reverse of what was observed in the field (Figure 2-2 and Figure 2-3).

Table 2-1 Summary information from initial field survey immediately after the Lost Pines fire

Plot #	Soil Series/Texture	Fire Severity	Ash Depth (cm)	Measured SWR (M)			Organic Matter %
				Max	Min	Median	
Plot 1	Rosanky/sandy clay loam	Heavy	1.12	3.08	0.17	1.37	2.88
Plot 2	Rosanky/sandy clay loam	Heavy	0.79	2.06	0.17	1.37	3.22
Plot 3	Rosanky/sandy loam	Heavy	1.03	3.08	1.37	1.37	1.73
Plot 4	Robco/sandy clay loam	Moderate	0.86	1.37	0.69	0.69	3.32
Plot 5	Robco/sandy clay loam	Light	0.34	0.69	0.00	0.34	2.55
Plot 6	Robco/sandy loam	Light	0.21	0.69	0.34	0.34	1.93
Plot 7	Robco/sandy loam	Heavy	1.22	2.06	0.34	1.37	1.66
Plot 8	Robco/sandy clay loam	Heavy	1.14	2.06	0.34	0.69	2.16
Plot 9	Robco/ sandy clay loam	Heavy	0.76	2.06	0.34	0.69	1.72
Plot 10	Robco	Heavy	0.37	1.37	0.34	0.69	
Plot 11	Robco	Heavy	0.86	2.06	0.34	0.69	
Plot 12	Robco	Heavy	2.89	1.37	0.34	0.69	

Measured soil water repellency was greatest on heavily burned plots of Rosanky soil and lowest on the lightly burned plots.

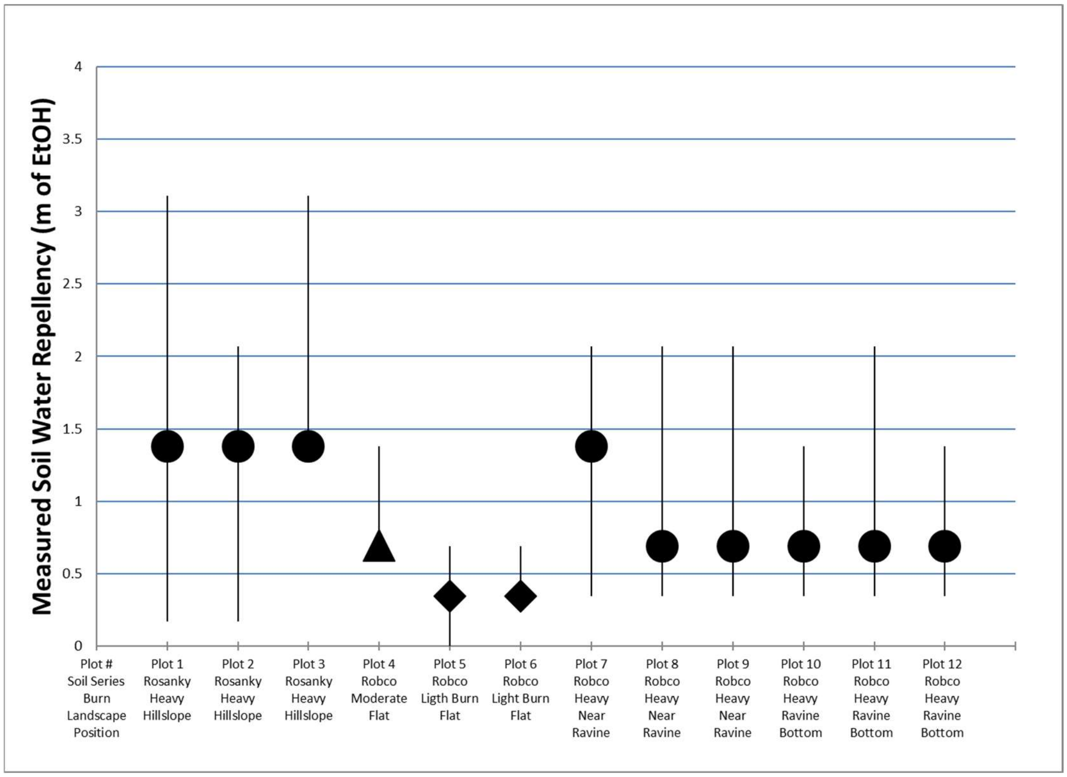

Figure 2-1 Median and range of soil water repellency measured immediately after the fire

Table 2-2 Multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner procedure / Two-tailed test:

Sample	Frequency	Sum of ranks	Mean of ranks	Groups*					
Plot 5 - Robco Light Burn	25	1295.000	51.800	A					
Plot 6 - Robco Light Burn	25	1849.500	73.980	A	B				
Plot 12 - Robco Heavy Burn	17	1583.500	93.147		B	C			
Plot 10 - Robco Heavy Burn	20	2169.000	108.450		B	C	D		
Plot 8 - Robco Heavy Burn	25	3332.000	133.280		B	C	D	E	
Plot 9 - Robco Heavy Burn	25	3876.500	155.060			C	D	E	
Plot 11 - Robco Heavy Burn	25	3896.500	155.860			C	D	E	
Plot 2 - Rosanky Heavy Burn	25	3948.500	157.940			C	D	E	
Plot 4 - Robco Moderate Burn	25	3953.500	158.140				D	E	
Plot 7 - Robco Heavy Burn	25	4714.500	188.580					E	F
Plot 1 - Rosanky Heavy Burn	25	4785.000	191.400					E	F
Plot 3 - Rosanky Heavy Burn	23	5351.500	232.674						F

**Letters indicate statistically distinct groups. These grouping indicate that immediately after the fire soil water repellency was weakly correlated with fire intensity*

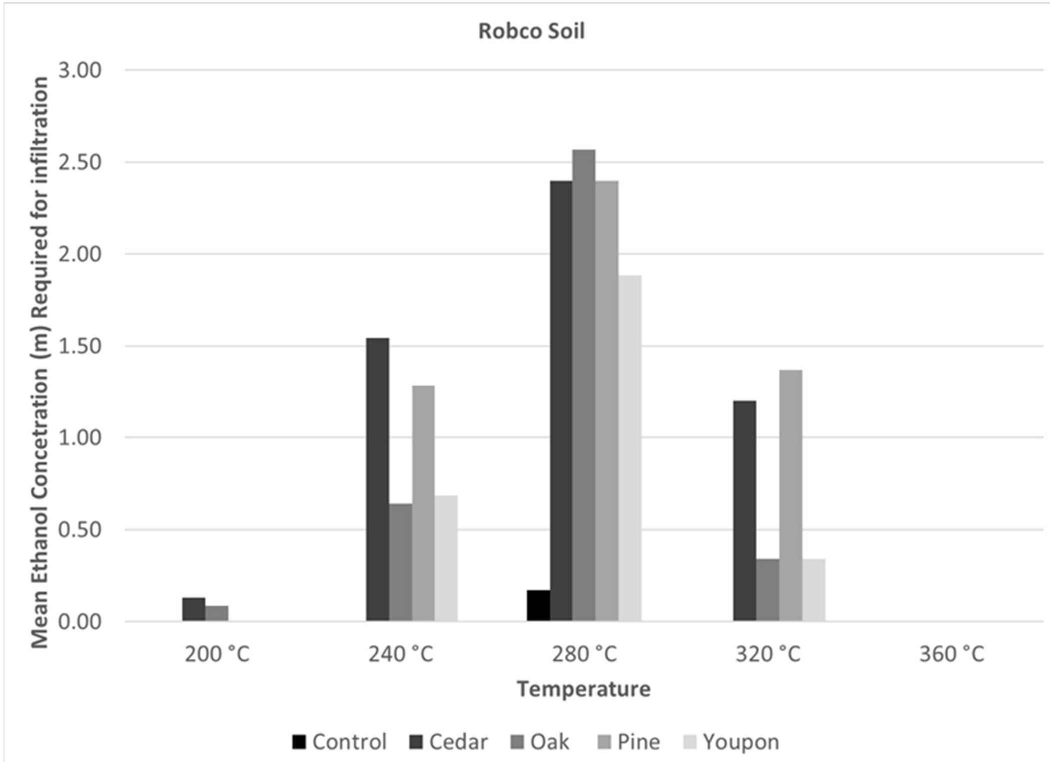

Figure 2-2 Mean measured laboratory induced soil water repellency for Robco sampled soil

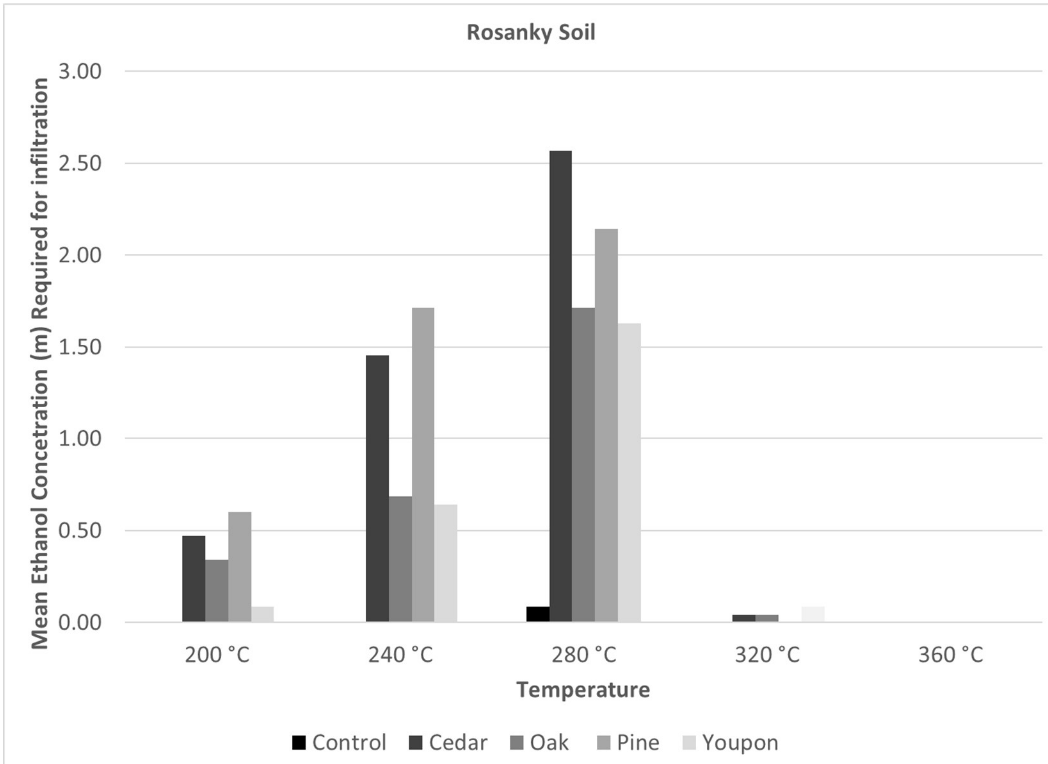

Figure 2-3 Mean measured laboratory induced soil water repellency for Rosanky sampled soil

2.3.2. Variation among plant species

The second component of the laboratory heating experiments was an effort to determine which of the species present in the Lost Pines was likely to contribute to the formation of a water-repellent layer. The ANOVA (Addinsoft, 2019) results indicate that the soil type, vegetation type, and temperature were all significant variables.

Table 2-3 ANOVA analysis of laboratory heating experiment.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Soil Type	1	1.437	1.437	4.599	**0.033**
Vegetation	4	41.053	10.263	32.843	**< 0.0001**
Sample Size	1	0.676	0.676	2.163	0.142
Temperature	4	117.168	29.292	93.737	**< 0.0001**

P-values indicate that soil type, vegetation type, and temperature were significant variables, while sample size was not

Tukey's highest significant difference test was used to compared the response of the four vegetation types. All induced water repellency, but Eastern Red Cedar produced the greatest level of water repellence, followed by the Loblolly Pine. These findings have significant management ramifications because eastern red cedar has long been viewed as an invasive nuisance species (Smith 2011). The potential for cedar to induce water repellency in soils is yet another reason for land managers to advocate for its removal.

Table 2-4 Vegetation / Tukey (HSD) / Analysis of the differences between the categories (Soil Water Repellency) –

Category	LS means	Standard error	Lower bound (95%)	Upper bound (95%)	Groups*			
Control	0.028	0.062	-0.095	0.151	A			
Yaupon	0.518	0.062	0.395	0.641		B		
Oak	0.619	0.062	0.496	0.742		B	C	
Pine	0.843	0.062	0.721	0.966			C	D
Cedar	0.946	0.062	0.823	1.069				D

**Letters indicate statistically distinct groups. All four vegetation types induced soil water repellency, but to differing degrees.*

The soil water repellency values measured in the laboratory were regressed against the infiltration values recorded for the same samples. This was done to establish a predictive relationship between the SWR and infiltration. The two soil types were regressed separately. Both regressions generated statistically significant relationships (p-value <0.001). The lowest rates of infiltration are found in the samples heated at 280°C, while are fastest rates are found in the samples heated to 360°C.

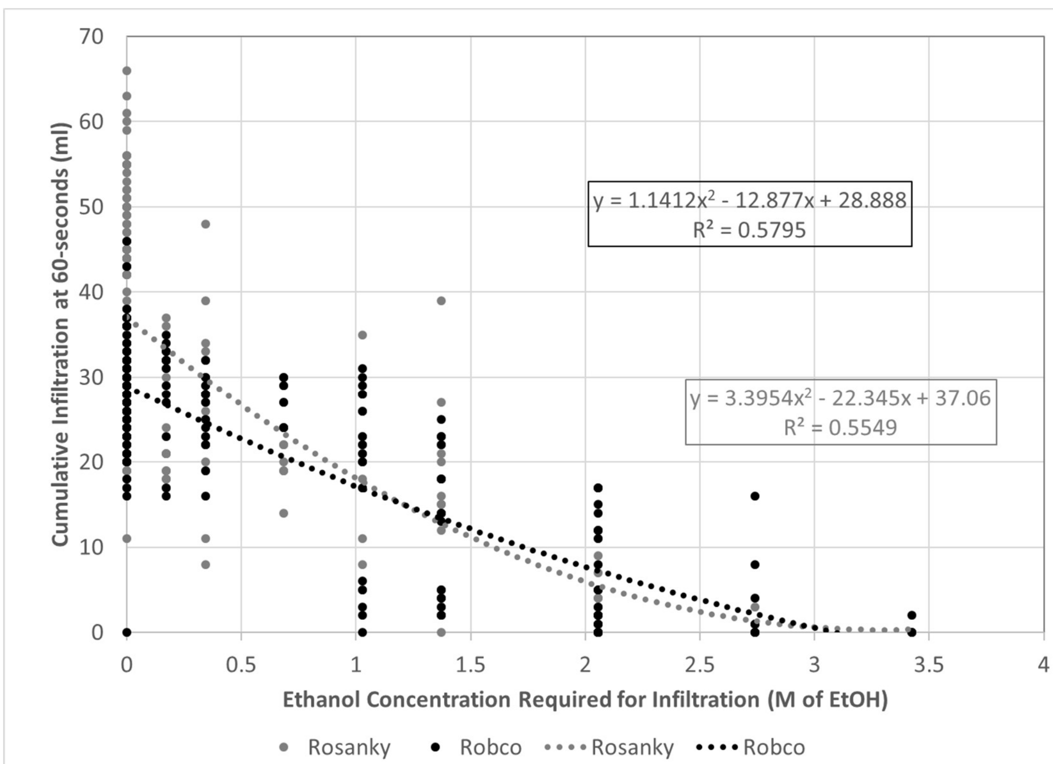

Figure 2-4 Laboratory induced SWR vs 60-sec cumulative infiltration

It is noteworthy that the strong correlation between measured soil water repellency and unsaturated hydraulic conductivity observed in the laboratory, was not persistent across multiple wetting/drying cycles. In the laboratory studies where water repellent soils were wetted and allowed to dry, measurable water repellency did sometimes return. But when unsaturated hydraulic conductivity was measured on those previously wetted soils, the strong correlation that was observed earlier was no longer present. The lack of a correlation between soil water repellency and hydraulic conductivity measured in the field is consistent with laboratory findings given that we were not able to measure hydraulic conductivity until several months after the fire, and after the soils' first post-fire wetting.

It appears that at least in these soils, that although measurable soil water repellency may persist through multiple wetting/drying cycles, after the first wetting the water repellency becomes too fragmented or patchy to have a significant effect on water infiltration.

The established laboratory relationships between temperature, vegetation type, and soils type, and even the strong correlation between SWR and infiltration are consistent with the establishment of a water-repellent layer resulting from the condensation of hydrophobic compounds onto the soil surface.

2.3.3. Coordinating lab and field data over time and space

After establishing strong relationships between SWR and temperature, soil type, vegetation, and infiltration in the laboratory, we anticipated finding similar relationships in the field observations. At any given spot, the formation of a water-repellent layer during a fire is dependent upon several factors, including but not limited to fire intensity, fuel supply, leaf litter composition, soil moisture, soil texture and soil structure. Given the natural variability in these factors, it is reasonable to expect spatial variability in post-fire soil water repellency. We hypothesized that by collecting data on the various environmental factors, we would be able to create an empirical model allowing us to forecast SWR and by extension, infiltration. We expected that the SWR would decay over time and become increasingly patchy as time progressed, and we anticipated that it would persist longest in the heavily burned plots with Robco soil.

However, in the months following the fire, the transient nature and spatial heterogeneity of fire induced SWR made it very difficult to characterize, and patterns within the data were difficult to identify. As the summer passed it became increasingly apparent that the removal of vegetation had completely altered by the hydrologic balance at the site. Measurement of soil water repellency using the MED methodology is known to be affected by soil water content, and even atmospheric humidity. Our lack of ability to control for soil moisture in the field undermined our ability to assess SWR, or even to determine which is the cause and which is the effect.

The field data collected from the study site showed that no water repellency existed after the initial autumn rains or during the wet winter months. Water repellency did return the following summer once the soil had sufficiently dried from winter and spring rains. Once the soil water repellency had returned, it slowly decreased over the course of the hot dry summer months, and by the one-year anniversary of the fire only minimal repellency existed. Studies of the longevity of fire induced water repellency are rare, but the approximate 13-month persistence of the observed water repellency is generally in line with other studies (Doerr and Moody 2004).

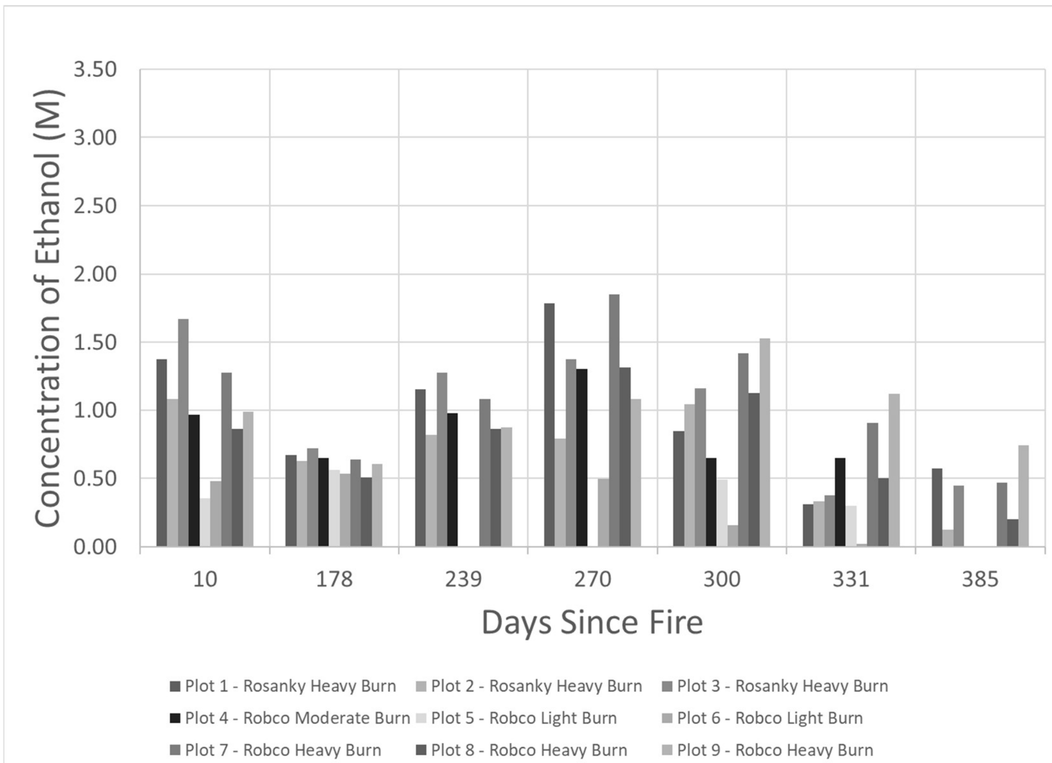

Figure 2-5 Mean Post-fire Soil Water Repellency

The SWR on the lightly burned plots was the last to return in the summer months and quickest to fade away as the summer passed. The plots with the highest SWR immediately following the fire generally had higher measured SWR over the course of the year. But neither of these general trends was completely was consistent or uniform. No significant difference existed between the two soil types in the field.

Despite the strong correlation in the laboratory, no significant correlation between measured soil water repellency and infiltration as measured by the minidisk infiltrometer was observed in the field. In fact, the trend was reverse. While measurable water repellency still existed on the heavily burned plots throughout the summer months, measured water conductivity rates were frequently highest on the heavily burned plots.

We anticipated that the soil water repellency would become increasingly fragmented and patchy as time passed. The Moran's I analysis was used to evaluate the spatial connectivity of the data collected. During the first sampling event only five of the nine plots analyzed exhibited a significant degree of spatial connectivity. As time passed that number steadily dropped to zero before rebounding slightly in the last sampling event. The overall decrease in spatial auto correlation across the study time period confirms the second hypothesis that the SWR would become increasingly patchy with time. But, since only slightly more than half the plots exhibited positive autocorrelation even in the first sampling event, it seems likely that sampling was done at the wrong spatial scale.

Evaluating fire intensity is only possible at a very coarse qualitative level. And with the natural variability and randomness of soil texture, animal burrows, root channels, litter composition, etc., in retrospect it seems unlikely that real spatial gradients at the 1-meter scale or even the 10cm scale can be identified with the sample grids. Furthermore, the MED sampling methodology used here typically involved gently clearing a small area, approximately 5cm by 5cm and placing a series of ethanol solution drops on the soil surface. In all cases, the recorded data reflects the highest level of water repellency observed within the sample square. Anecdotally, during the first sampling event immediately after the fire, the observed water repellency was nearly uniform across the small 5cm x 5cm sample square. But as time passed more variability within the small sampling square became apparent.

Table 2-5 Moran's I statistic. Significant values ($p<0.05$) are bolded and indicate significant spatial autocorrelation*

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7	Plot 8	Plot 9
Sep 2011	0.14	**0.21**	-0.12	-0.07	**0.49**	**0.25**	**0.47**	**0.42**	0.25
Mar 2012	0.07	-0.01	0.12	-0.07	**0.32**	**0.25**	-0.02	**0.32**	**0.38**
May 2012	0.08	**0.33**	-0.19	-0.08			**0.38**	**0.19**	0.14
Jun 2012	**0.30**	0.01	**0.17**	**0.50**		-0.09	-0.10	-0.10	-0.10
Jul 2012	0.13	-0.04	-0.11	-0.02	0.09	**0.30**	0.10	0.19	-0.01
Aug 2012	-0.13	-0.17	0.03	0.02	-0.05	0.03	0.11	-0.16	-0.09
Sep 2012	0.12	-0.16	**0.29**				**0.19**		

**Moran's I values range from 1 to -1. Values near 1 indicate a strong spatial correlation while value near -1 indicate negative correlation. Values near 0 indicate spatial randomness. Here the number of plots exhibiting significant positive spatial autocorrelation decreases as time passes*

Is easy perhaps, to conclude that our inability to control for soil moisture was the primary factor that led to the inability to produce a viable deterministic model. However, it is easy to fall into a trap of believing that if we only had data for one more variable that we would be able to unravel the secrets of the universe. In retrospect, the natural heterogeneity, and chaotic nature of precipitation and especially fire itself deeply undermine, and likely preclude efforts to successfully model SWR at this scale. The observed behavior also points at the possibility of other mechanisms, such as the incorporation of ash and char, contributing to SWR in the post-fire environment.

Figure 2-6 Bank erosion near Plot 7, December 2011

2.3.4. Post-fire Revegetation

The study site experienced severe erosion in the first few months after the fire, but by the following summer, the most visible difference on the study site was the varying re-vegetation rates (Appendix 1). The first natural re-vegetation occurred about four months after the fire in Plot 5 and Plot 6, the two lightly burned plots. Significant vegetation did not return to the other plots until late spring 2012, nearly eight months after the fire. The vegetation on all plots that first year was dominated by a series of small unidentified grasses and forbs, and pokeberry (*Phytolacca americana*) which had never been observed on the property before. It is a safe assumption that the seeds for the grasses and forbs was blown in by the winds, while the pokeberry seeds were deposited by birds. It is impossible to conclude that the differences in seed germination/re-vegetation were simply due to the water-repellent nature of the soils in the heavy burned plots, but its plausible that the reduced soil moisture, and increased run-off typically associated with SWR played a role in impaired vegetation recovery.

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3. INCORPORATION OF CEDAR ASH AND CHAR AS A MECHANISM TO INDUCE SOIL WATER REPELLENCY

3.1. Introduction

A common occurrence during severe wildfires is the formation of water-repellent soils. Soil water repellency prevents water from entering the soil profile, which can hinder fire restoration efforts by stunting germination and revegetation, or it may also lead to an increase in runoff and erosion. Water repellent soils are thought to form as the result of volatilization of hydrophobic compounds in leaf litter. The hydrophobic compounds subsequently re-condense on soil particles, essentially giving soil a waterproof coating. However, the complex and often non-linear behavior of water-repellent soil in the weeks and months following a fire hints at other contributing mechanisms. This paper is an effort of explore the potential of ash and char to contribute to water repellent behavior in soils.

Wildfires consume plant matter (wood, roots, leaves, leaf litter, duff, etc.) leaving behind a blanket of ash (Balfour 2015). Fire's ability to create permanent or long-term changes in soil is driven primarily by the creation of ash (Certini 2005, Certini 2014). Within the fire research community, the term ash is used as a broad term used to describe a heterogeneous mixture of a spectrum of combustion products including an organic fraction derived from the combustion of organic matter, and an inorganic residue. (Marion, Moreno et al. 1991, Cerdà and Doerr 2008, Pereira, Cerdà et al. 2013, Bodí, Martin et al. 2014, León, Echeverría et al. 2015). However, it is crucial to differentiate between these products because they have such different chemical and physical properties. The organic fraction of ash is part of the black carbon continuum which includes fire-altered organic matter ranging from partially charred vegetation to char and charcoal to soot (Goldberg 1985, Masiello 2004, Bodí, Martin et al. 2014). The mineral ash, is composed primarily of silicates, oxides, and carbonates, that either exist within the plant as primary minerals, or undergo a transformation as a result of the fire. The depth and continuity of ash and char is known to vary spatially within a burn area primarily a function of the pre-fire fuel load. (Lavee, Kutiel et al. 1995, De Luis, González-Hidalgo et al. 2003, Cerdà and Doerr 2008, Woods and Balfour 2008, Balfour and Woods 2013). Moreover, the nature of the ash produced, and the ratios of the various combustion products is dependent upon the fire temperature.

Char, the residue of incomplete combustion of vegetation, is produced at temperatures between 250°C and 450°C (Baldock and Smernik 2002, Certini 2005, Schmidt, Torn et al. 2011). Char created at temperatures below 350°C can be either hydrophobic or hydrophilic. Below 250°C dehydration reactions dominate. Between 250°C and 300°C the loss of oxygen, hydrogen, and nitrogen lead to the formation of aromatic functional groups within the remaining organ matter. Hydrophobicity in char is strongly correlated with the presence of unsaturated hydrocarbons containing aromatic, aliphatic, and carboxylic functional groups (Almendros, Knicker et al. 2003, Kuo, Herbert et al. 2008, Dlapa, Bodí et al. 2013). As temperature increases from 350°C to 450°C, oxidation continues, the ash becomes lighter in color, and the ratio of organic carbon to carbonates declines as the ash becomes hydrophilic (Quill, Angove et al. 2010, Hogue and Inglett 2012, Balfour and Woods 2013). Above 450°C organic compounds are almost completely combusted, leaving a light gray or white colored mineral ash composed of silica and carbonate compounds (Ulery and Graham 1993, Goforth, Graham et al. 2005). Ash produced at temperatures above 900°C contains mainly silica and oxides (Goforth, Graham et al. 2005, Quill, Angove et al. 2010, Pereira, Úbeda et al. 2012).

Ash can be incorporated into the soil by downward migration becoming a permanent part of the soil profile, changing the physical and chemical properties of soils and affecting the infiltration of water into the soil column (Raison 1979, Raison, Khanna et al. 1985, Alexis, Rasse et al. 2007, Úbeda, Pereira et al. 2009, Arkle and Pilliod 2010, Bodí, Mataix-Solera et al. 2011, Gabet and Bookter 2011, Stoof, Vervoort et al. 2012, Pereira, Ubeda et al. 2013). Char may persist in soils for centuries (Schmidt and Noack 2000, Baldock and Smernik 2002, Certini 2005, Schmidt, Torn et al. 2011), so that its effects persist long after much of the ash has been removed from the soil surface by wind and runoff. Ash has sometimes been shown to increase soil water retention, but it also has been reported to reduce infiltration by clogging pores (Stoof, Wesseling et al. 2010, Woods and Balfour 2010, Bodí, Doerr et al. 2012, Ebel 2012, Ebel, Moody et al. 2012).

The study of ash produced by wildfire presents some unique challenges. The ash layer that exists immediately after a fire is generally not persistent in the environment and is often rapidly redistributed and removed from burn sites by wind and runoff before field studies can begin (Mataix-Solera, Guerrero et al. 1999, Cerdà and Doerr 2008, Pereira, Cerdà et al. 2013). Wildfire studies tend to focus on the more readily apparent and easily quantified factors such as soil erosion, soil water repellency, and revegetation that affect land restoration and forest management efforts.

This paper couples field measurements and observations taken after a large wildfire with laboratory studies in an effort to investigate the potential of incorporated ash and char to affect persistent changes on soil hydrologic properties. Specially, these experiments were designed to test the hypothesis that incorporation of hydrophobic char into the soil profile would induce water repellent behavior in soil. The specific objectives of this research are to (1) determine the viability of the hypothesized mechanism – soil water repellency induced through incorporation of char, and (2) investigate the persistent or longevity on induced effects, and (3) investigate the role of particle size of incorporated ash/char in inducing soil water repellent behavior in the post-fire environment.

3.2. Methods

3.2.1. Study Site

The Lost Pines Forest is a unique 13-mile belt of loblolly pines (*Pinus taeda*) in Bastrop County, Texas. This small isolated belt of pine tree is separated by more than 100 miles from Piney Woods region that covers parts of Texas, Arkansas, Louisiana, and Oklahoma. The Lost Pines is thought to be the remnant of a much larger pine forest that shrank in size during the last glacial period of the Pleistocene era (Al-Rabab'ah and

Williams 2004). In addition to the loblolly pine the primary species in Lost Pines Forest are Black Jack Oak (*Quercus marilandica*), Eastern Red Cedar (*Juniperus virginiana*), and Yaupon Holly (*Ilex vomitoria*).

The Lost Pines fire was a major wildfire that struck Bastrop County, Texas, in September and October 2011. Wildfires are not uncommon in the Lost Pines area, but this fire is noteworthy for both its size and intensity. The fire started on September 4, 2011 and burned in a southerly direction forming a progressively widening strip located east of the city of Bastrop. The fire was preceded by a year of extreme drought. The area had not received significant rainfall in over a year prior to the fire. Circumstances were further exacerbated by Tropical Storm Lee, which produced strong winds in central Texas, creating ideal conditions for wildfires to spread. A total of 33,418 acres were burned (LPRT 2011).

The Bastrop fire presented a unique opportunity to study fire-altered soils. A series of study plots were established on a property within the burn zone. The property is located, immediately north of the intersection of Park Road 1C and Cottletown Road. Fire burned through the area on September 5^{th} and the property contains patches of various fire severities. A steep ravine bisects the property. The area west of the ravine was severely burned while the area east of the ravine is a mix of severe, moderate, and lightly burned patches. Prior to the fire the area was covered with mixed forest.

Figure 3-1 Post burn study site near Plot #7 (Sept 2011).

3.2.2. Field Data Collection

Twelve four-meter by four-meter grids were established on the research property to establish plots in different landscape positions, fire intensity, and type of vegetation. Nine of the 12 plots were placed in heavily burned areas with three plots each on a small hilltop, next to the ravine, and at the bottom of the ravine. Two plots were placed in lightly burned areas, and one was placed in a moderately burned area. Soil fire intensity was determined using USDA guidelines (Parsons, Robichaud et al. 2010).

Ash depth was measured at the meter nodes for each plot so that 25 samples were taken from each plot. The ash depth on the soil surface was measured used a common ¾-inch soil sampler and a hand-held ruler. The ash sampled frequently contained a mix of mineral ash, charred vegetation, and no attempt was made to differentiate the two as measurements were taken. Photographs of the ground surface in each plot were also taken.

Figure 3-2 Soil Sampler and handheld ruler used to measure ash depth

As expected, the greatest ash depth was found on the heavily burned plots. In the heavily burned plots, the measured layer consisted of a mix of ash and charred leaf litter. In the light burn plots the measured layer consisted primarily of charred leaf litter. Ash accumulation was generally not observed on these plots. Measuring ash depth on the plots located at the bottom of the ravine proved to be problematic. Very little accumulated leaf litter existed at the bottom of the ravine prior to the fire, and in most spots the soil there was very shallow. Where bare rock was exposed no data was recorded. In addition, the surface of the ravine plots was very uneven, and ash was observed to have preferentially accumulated in low spots of the plots.

3.2.3. Laboratory Study

3.2.3.1. Incorporation of Mineral Ash and Char into soil (Lab Experiment A)

Downward movement of ash and char into the soil profile was observed at the Bastrop burn site in the months following the fire. It was hypothesized that this process may contribute to persistent water-repellent behavior fire-affected soils. In order to assess the viability of this mechanism to bring about soil property changes, small amounts of ash and char were mixed with soil to mimic the phenomenon observed in the field.

Ash was created by heating cedar needles at either 240°C, 280°C, 320°C, 360°C, 400°C, or 440°C, for two hours. Two grams of material from each temperature was mixed with 10g of Robco soil. The soil was collected from an unburned area of the field site. The soil was air dried and passed through a #30 sieve to remove any gravel or large plant debris. The soil/ash mixture was added to the top of 190g of unheated soil in a series of small steel cans. Six replicate samples for each temperature were prepared, for a total of 36 samples with three additional control samples.

Because the soil in this procedure is unheated, soil in this experiment had no measurable water repellency according to the MED methodology. So, water repellency was assessed by using the mini-disk infiltromer set at -2.0 cm of tension (Decagon Devices, Pullman WA). The use of the mini-disk infiltromer is a well-established method for collecting data in fire-affected soils (Robichaud, Lewis et al. 2008, Woods and Balfour 2008, Moody, Kinner et al. 2009, Balfour 2015). Measurements were taken at 10-second intervals for the first 60 seconds. After the first 60 seconds, measurements were taken at 60 seconds intervals until 15 minutes had elapsed or infiltration ceased.

To determine if any effects created by the incorporation of ash into the soil were persistent, the soil samples were dried after the initial measurement, and the measurement process was repeated three additional times. The soils were dried by placing them in at oven at 70°C for four hours. This process was repeated so that infiltration was measured four times for each sample.

3.2.3.2. Incorporation of sieved ash (Lab Experiment B)

Ash has been speculated to reduce water infiltration by clogging soil pores as it becomes incorporated into the soil profile (Stoof, Wesseling et al. 2010, Bodí, Martin et al. 2014). If ash does reduce infiltration by clogging soil pores, the effect should be highly dependent upon and the grain size of the ash. To test this concept, an additional experiment was preformed where ash was sieved prior to incorporation into the soil. Cedar needles were heated for two hours at either 280°C, 380°C or 480°C. After heating the ash and char were sieved using a #35 (0.5 mm), #120 (0.125 mm), and #270 (0.053 mm) sieve. Two grams of material from each temperature and sieve size was mixed with 10g of Robco sampled soil. The soil was air-dried and sieved as described in the earlier experiment. As before the soil/ash mixture was added to the top of 190g of unheated soil. Each size and temperature combination were replicated four times.

As before in the previous experiment, hydraulic conductivity was measured for each sample using the mini-disk infiltrometer. Measurements were taken at 10-second intervals for the first 60 seconds, and then once every 60-seconds until infiltration had ceased.

3.3. Results

The measured ash depth corresponded reasonably well to the fire severity (Table 3-1). The two lightly burned plots had the thinnest measurable ash layer of any of the 12 plots, while the previously heavily wooded plots near the ravine (Plots 7-9) had the thickest measurable ash layer (Fig. 3-3). Because a Shapiro-Wilk test concluded that the ash depth data measured in the field was not normally distributed (Shapiro and Francia 1972), a Kruskal-Wallis test was performed, rather than the more traditional one-way ANOVA, to determine is significant differences existed between plots (Kruskal and Wallis 1952). The statistical analysis of the ash depth indicated that significant differences existed amongst the plots (Table 3-2). Pair-wise comparisons showed that both light burn plots, Plot 5 and Plot 6, had significantly less accumulated ash than the other plots, and were grouped together, while the remaining plots were clustered in two over-lapping groups (Table 3-3). Plots 10 through 12 were excluded from this analysis because of the incomplete nature of the data sets from those plots.

The photographs of the study plots demonstrate the variability amongst the plots found at the study site, and it is possible to compare the burn severity of the various plots just from the photographs (Figure 3-4).

Table 3-1 Summary information for field plots and ash depth

Plot #	Soil Series	Burn Severity	Landscape Position	Ash Depth (cm)		
				Minimum	Maximum	Mean
Plot 1	Rosanky	Heavy Burn	Hillside	0	2	1.1
Plot 2	Rosanky	Heavy Burn	Hillside	0.1	2	0.8
Plot 3	Rosanky	Heavy Burn	Hillside	0.3	2	1
Plot 4	Robco	Moderate Burn	Flat	0.5	2	0.9
Plot 5	Robco	Light Burn	Flat	0.1	1	0.3
Plot 6	Robco	Light Burn	Flat	0	1	0.2
Plot 7	Robco	Heavy Burn	Near Ravine	0.5	2	1.2
Plot 8	Robco	Heavy Burn	Near Ravine	0.5	3	1.1
Plot 9	Robco	Heavy Burn	Near Ravine	1	2	1.3
Plot 10	Robco	Heavy Burn	Ravine Bottom	0.1	1	0.4
Plot 11	Robco	Heavy Burn	Ravine Bottom	0.1	3	0.9
Plot 12	Robco	Heavy Burn	Ravine Bottom	1	4	2.9

As might be expected the thickest ash layers were found near the ravine, an area that had been heavily wooded prior to the fire. By comparison very little ash was found on the lightly burned plots immediately after the fire.

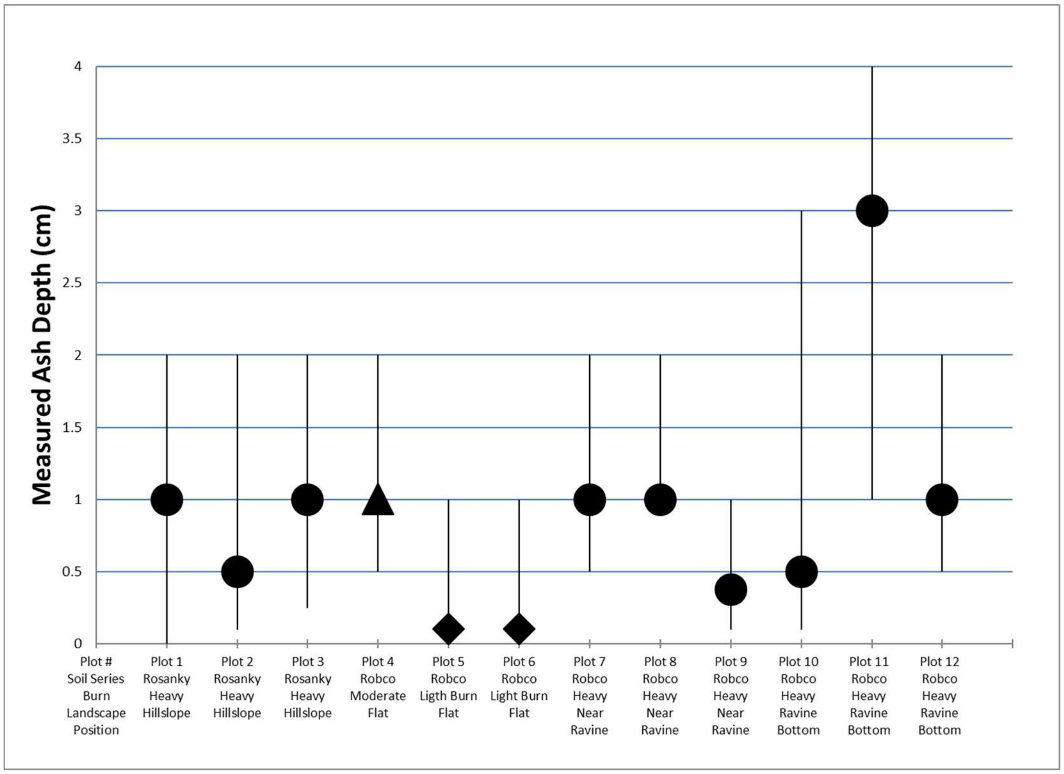

Figure 3-3 Median and range of measured ash depth (cm) immediately after the fire

Table 3-2 Kruskal-Wallis test – Ash Depth:

Kruskal-Wallis test / Two-tailed test:	
K (Observed value)	100.071
K (Critical value)	15.507
DF	8
p-value (one-tailed)	< 0.0001
alpha	0.05

P-value indicates that significant difference exists between the plots

Table 3-3 Multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner procedure / Two-tailed test:

Sample	Frequency	Sum of ranks	Mean of ranks	Groups*		
Plot 6	25	814.000	32.560	A		
Plot 5	25	1212.000	48.480	A		
Plot 2	25	2497.500	99.900		B	
Plot 4	25	2785.500	111.420		B	C
Plot 3	25	3154.000	126.160		B	C
Plot 1	25	3229.500	129.180		B	C
Plot 8	25	3495.500	139.820		B	C
Plot 7	25	3718.000	148.720			C
Plot 9	15	2314.000	154.267			C

** Letters identify statistically distinct groups. Significantly less ash was present on the two lightly burned plots, Plots 5 and 6.*

Figure 3-4 Photographs of study plots – September 2011

Plot 1

Plot 2

Plot 3

Plot 4

Plot 5

Plot 6

Figure 3-5 Photographs of study plots – September 2011

Plot 7

Plot 8

Plot 9

Plot 10

Plot 11

Plot 12

In the months following the Lost Pines fire, an ash crust developed in a heavily burned potion of the study site near Plots 8 and 9. The ash crust is further evidence of the severity of the fire in this portion of study area. The crust forms as CaO formed by the fire reacts with moisture in the environment, to create $Ca(OH)_2$, leading to the solubilization of silica and a weakly cemented crust above soil surface (Bodí, Martin et al. 2014, Balfour 2015). The hydraulic conductivity of the observed ash crust was not measured, but others have found an order of magnitude drop as the result of ash crust formation (Balfour 2015).

Figure 3-6 An ash crust developed in the heavily burned areas of the study site after moisture re-entered the environment.

3.3.1. Ash incorporation

The ash incorporation experiments were undertaken to test the potential for ash and char created at various temperatures to become entrained into the soil profile, and affect persistent change on the soil's hydraulic properties.

In Experiment A, infiltration was measured four times on each sample with the samples dried between measurements. A two-way ANOVA was used to test for differences between the various temperatures to which the ash was heated. The test was also used to determine if differences existed as the samples progressed through each wetting and drying cycle.

The ANOVA indicated that there was clear difference between the various temperature treatments (Table3-6). Additional analysis using Tukey's HSD test grouped the temperature treatments into three overlapping groups with 240°C, 280°C, and 320°C on one end, and 360°C, 400°C, and 440°C on the other (Table 3-7). The control samples fell in between the two groups. These groupings coincide with previous published descriptions of ash and char created at these temperatures (Doerr, Dekker et al. 2002, Dlapa, Bodí et al. 2013). The soil water repellency increases from 240°C to 280°C, and then begins to fade as the temperature approaches 320°C. Somewhere between 320°C and 360°C the char crosses a threshold and soil water repellency is gone. The measured infiltration for the samples with ash created at 360°C, 400°C, and 440°C are remarkable similar, with only slight differences.

This data clearly demonstrates the ability of ash and char to affect changes in soil hydrology. It is however instructive to compare the infiltration values in this experiment to those measured in an earlier similar experiment (see Chapter 2). In that experiment, soil water repellency was induced by heating the soil with the vegetation. The mean 60-second infiltration for Robco sampled soil heated at 280°C with 2 grams of cedar in that experiment was 2.5 ml. By comparison, the lowest mean value recorded in this experiment was 8.0 ml on the third wet/dry cycle for char heated at 280°C. However, in contrast to the earlier experiment (see Chapter 2), here the induced water repellency persisted and even strengthen across wet/dry cycles.

The ANOVA indicted that significant difference did not exist amongst the wet/dry cycles, but significant interaction did occur between the two independent variables, temperature and wet/dry cycle. The significance of the interactions between the variables is an important finding. In examining the data with the hydrophilic char (240°C to 320°C) the infiltration is greatest in the first wet/dry cycle, and is then much lower during the second and third cycle (Figure 3-6). Speculatively, this indicates that as the char becomes further entrained into the soil it effectively reduces the permeability of the soil. By the forth cycle the effects of the char appear to have faded as the char is dispersed as it is pushed deeper into the soil profile.

By contrast, for soil in the other temperature grouping (360°C, 400°C, and 440°C), infiltration consistently measured above the control for the first three cycles. In other studies, ash has sometimes been shown to increase soil water retention, so theses finding are in line with other work (Stoof, Wesseling et al. 2010, Ebel, Moody et al. 2012). However, in the fourth wet/dry cycle the infiltration for all three temperatures dropped to levels similar to the control samples. The cause of this decreased infiltration during the fourth cycle is unclear. It may be that the porosity of these samples was so fragile that by the fourth wet/dry cycle it had collapsed, effectively counteracting the ash incorporation.

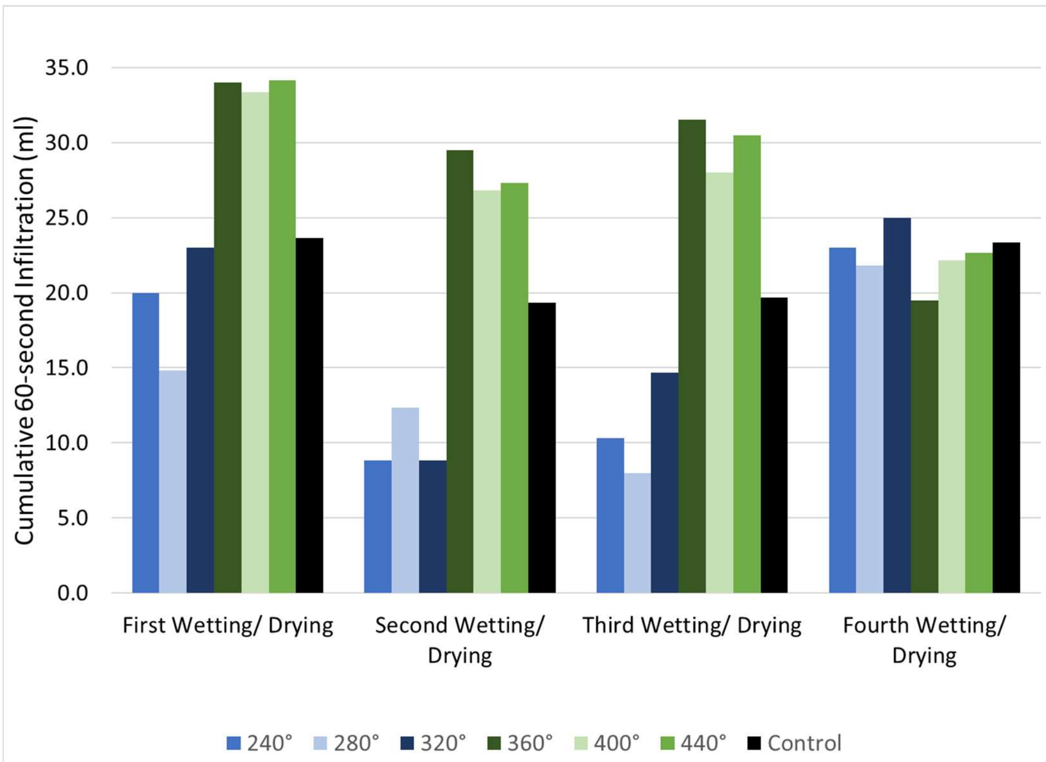

Figure 3-7 Cumulative infiltration at 60-seconds across multiple wet/dry cycles (Experiment A)

Table 3-4 Summary information for ash incorporation experiment (Experiment A)

Wetting/Drying Cycle	Mean Cumulative Infiltration (ml) at 60-seconds						
	240°	**280°**	**320°**	**360°**	**400°**	**440°**	**Control**
First Wetting/Drying	20.00	14.83	23.00	34.00	33.33	34.17	23.67
Second Wetting/Drying	8.83	12.33	8.83	29.50	26.83	27.33	19.33
Third Wetting Drying	10.33	8.00	14.67	31.50	28.00	30.50	19.67
Fourth Wetting/Drying	23.00	21.83	25.00	19.50	22.17	22.67	20.33

Six replications were performed for each measurement

Table 3-5 ANOVA table for ash incorporation experiment (Experiment A).

Source	DF	Sum of squares	Mean squares	F	Pr > F
Wet/Dry Cycle	3	0.328	0.109	2.236	0.087
Temperature	6	13.562	2.260	46.189	**< 0.0001**
Wet/Dry Cycle*Temperature	18	7.276	0.404	8.261	**< 0.0001**

Analysis indicates that Temperature variable was significant while, Wet/Dry Cycle was not, and importantly, that significant interaction existed between the two variables.

Table 3-6 Tukey (HSD) / Analysis of the differences between temperatures with a confidence interval of 95% (inf):

Temperature	Least Square means	Standard error	Lower bound (95%)	Upper bound (95%)	Groups*		
280	14.250	0.952	12.367	16.133	A		
240	15.542	0.952	13.659	17.425	A		
320	17.875	0.952	15.992	19.758	A	B	
Control	21.500	1.346	18.837	24.163		B	
400	27.583	0.952	25.700	29.466			C
360	28.625	0.952	26.742	30.508			C
440	28.667	0.952	26.784	30.550			C

* *Letters identify statistically distinct groups. The clear division indicates that a significant property change occurs in the char/ash between 320 and 360°*

The second ash incorporation experiment, Experiment B, was designed to test the effects of incorporation ash/char of various particle sizes. I hypothesized that the very fine-grained ash material may effectively clog soil pores as the ash becomes incorporated into the soil profile (Table 3-8). The ANOVA results for Experiment B indicated that both variables, temperate, and particle size were statistically significant (p-value <.05) (Table3-9). Interaction between the two variables was also significant, which is reasonable given that as the temperature of combustion increases, the ash/char particle size decreases. Additional Tukey's HSD test indicated that each size fraction was statistically different from the other (Table 3-10).

For the largest particle size (retained by #35 sieve), the mean infiltration for all temperatures was below the control, indicating that the coarse ash/char induced some level of water-repellent behavior regardless of temperature (Figure 3-7). At this size the particles are likely acting as a physical barrier to water entering the soil column. In the next size fraction (retained by #120 sieve), the ash/char material is roughly on par with the texture of the soil. At this size the ash/char mixture created at 480°C exhibited a classic infiltration curve with increasing infiltration at a decreasing rate (Figure 3-8). The 480°C curve is well above the control providing strong evidence for the hydrophilic nature of the ash/char created at that temperature. By contrast the ash/char created at 280°C exhibited an infiltration curve indicative of a water repellant soil, where infiltration is initially very slow, with the rate of infiltration gradually increasing after the first 60-seconds as the soil becomes wet. After the ash/char/soil mixture at the top of the column has become wet the slope of the two lines 480°C and 280°C are very similar.

Still, the total infiltration after 300 seconds for the 480°C material is nearly twice the infiltration for the material created at 280°C.

The infiltration curves for the material retained by the #270 sieve is shown in Figure 3-9. The greatest infiltration at for all three temperatures occurred at this size fraction. The behavior of the material created at 280°C is particularly unexpected and difficult explain in this size fraction. The hypothesized mechanisms do not account for the increased infiltration at this size fraction, and the data seems to indicate that there is some interaction between the soil and the ash/char at this size that is facilitating infiltration.

The infiltration curves from the smallest fraction are more straightforward (Figure 3-10). All three temperatures exhibited infiltration below of the control at this size fraction. At this size the ash/char/soil mixture at the top of the column is likely to have smaller pores than the soil below. This difference in porosity may prevent water from draining into the soil below until the matric potential of the top layer approaches zero, effectively creating a bottleneck at the top of the column. This may explain the shape of the 380°C curve in Figure 3-10. The 280°C ash/char at this size fraction effectively induces SWR until the top later is saturated.

Within this dataset there is clear evidence of what appears to be soil water repellency induced by incorporation of hydrophobic char (Figure 3-8), and in the same figure there appears to be evidence of hydrophilic ash increasing infiltration. There is also evidence of fine grain particles impeding infiltration (Figure3-10), and evidence of additional mechanism affecting soil hydrology (Figure 3-9). Clearly the interactions between soil and ash/char are both temperature and size dependent.

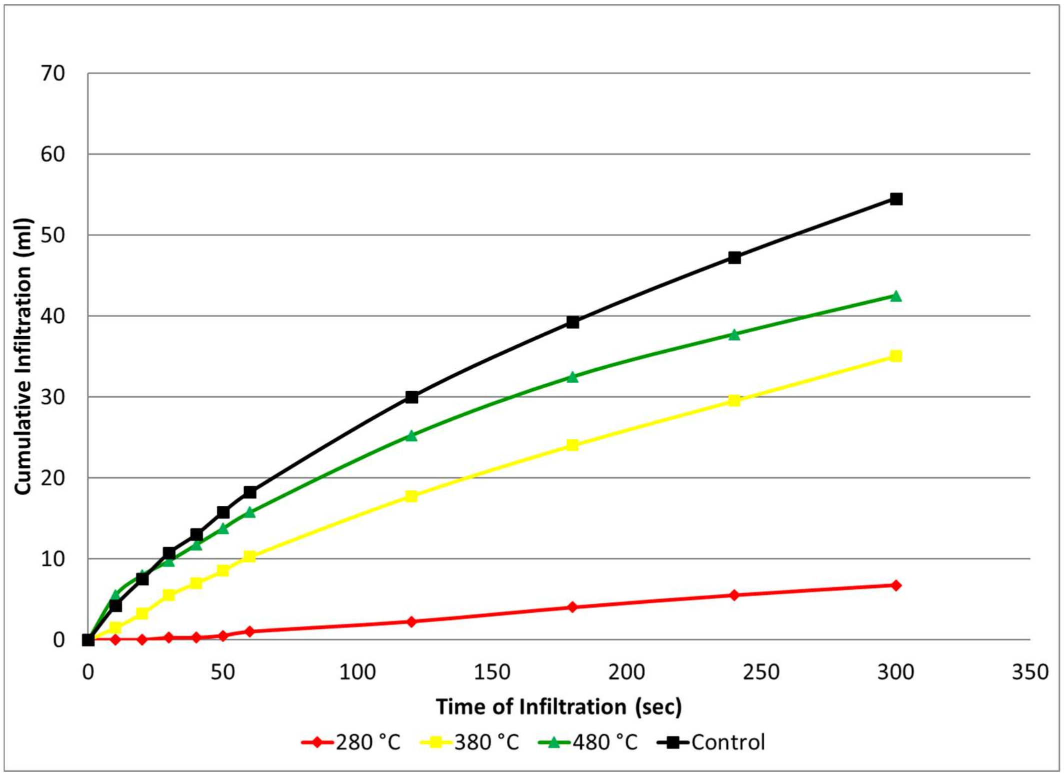

Figure 3-8 Cumulative infiltration of ash/char retained by #35 sieve

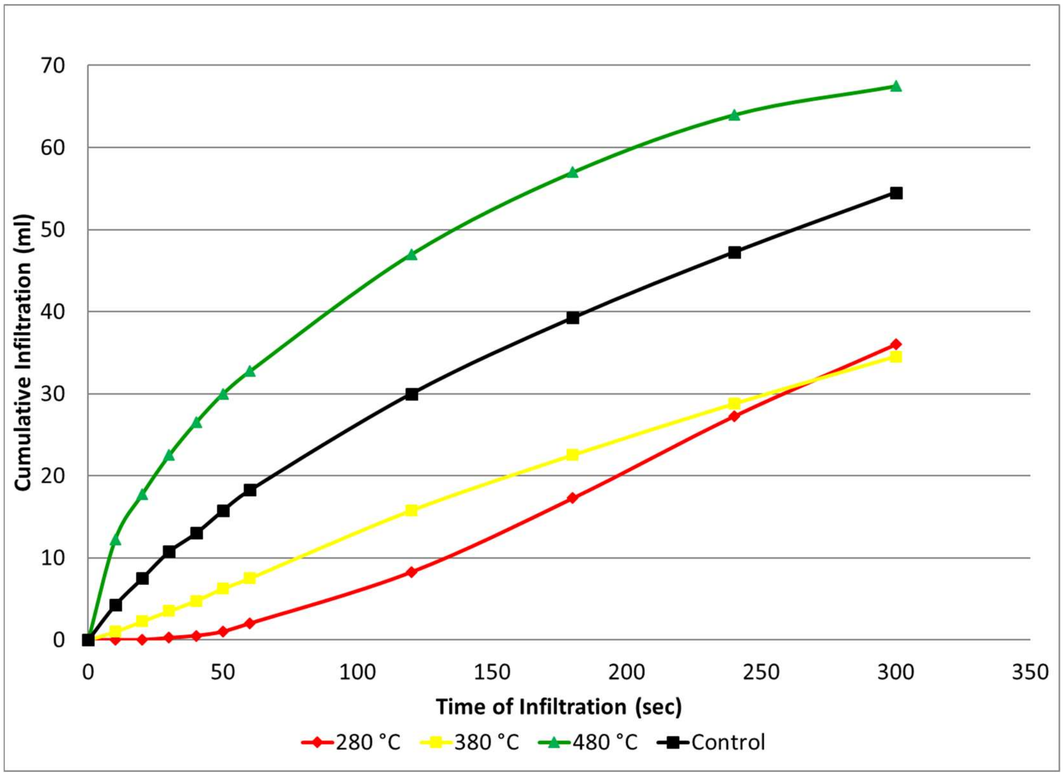

Figure 3-9 Cumulative infiltration of ash/char retained by #120 sieve

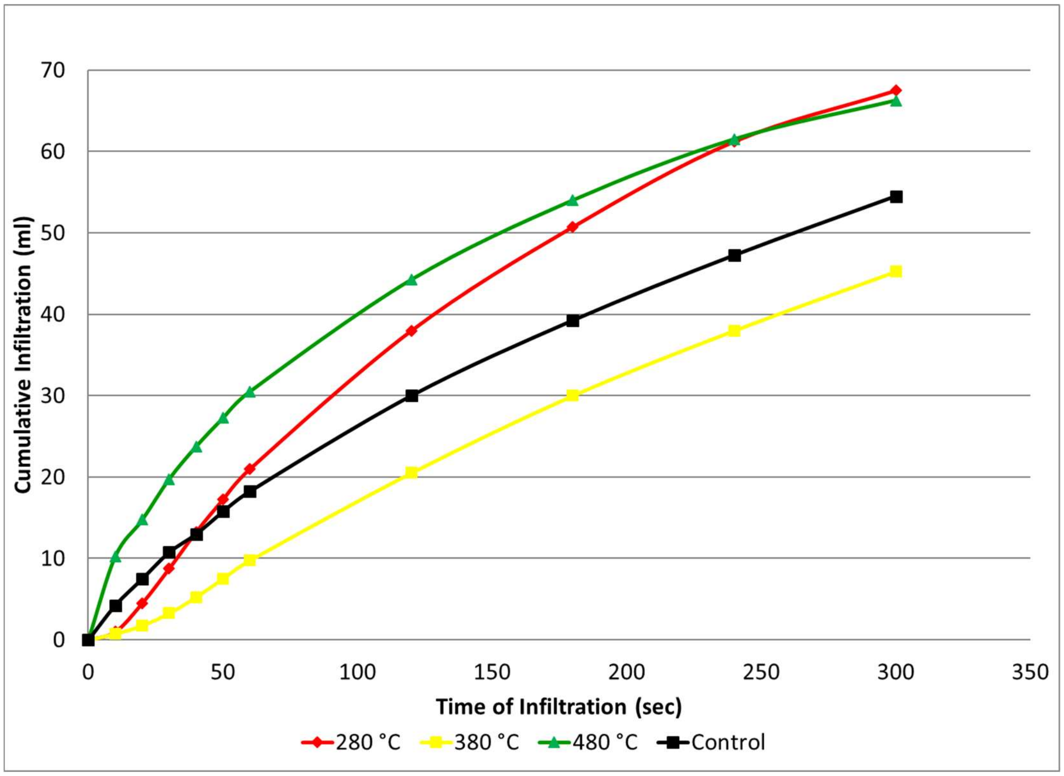

Figure 3-10 Cumulative infiltration of ash/char retained by #270 sieve

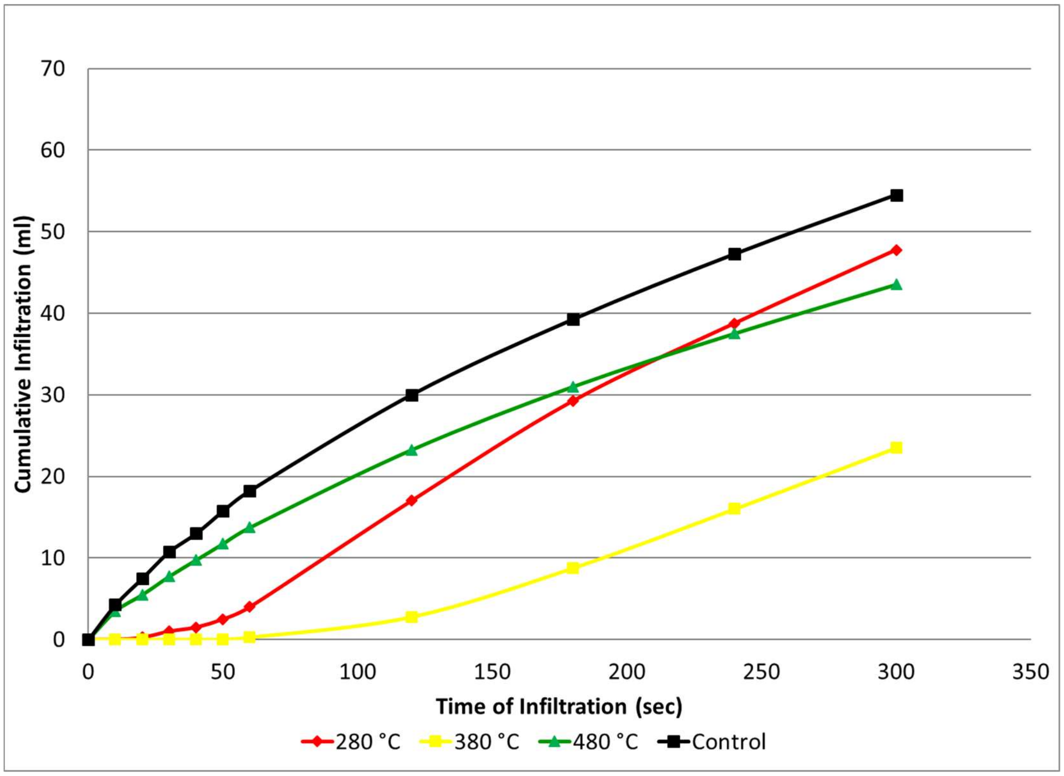

Figure 3-11 Cumulative infiltration of ash/char passed through #270 sieve

Table 3-7 Mean Cumulative infiltration at 60-seconds for ash sieved and incorporated into unheated Robco sampled soil.

Temperature	Mean Infiltration (ml) at 60-seconds				
	Retained by #35 Sieve (0.5mm)	Retained by #120 Sieve (0.125mm)	Retained by #270 Sieve (0.053mm)	Passed #270 Sieve	Control
280 °C	1.00	2.00	21.00	4.00	
380 °C	10.25	7.50	9.75	0.25	18.25
480 °C	15.75	32.75	30.50	13.75	

Four replications were performed for each measurement.

Table 3-8 ANOVA table for ash incorporation experiment (Experiment B).

Source	DF	Sum of squares	Mean squares	F	Pr > F
Particle Size	3	6382.167	2127.389	67.240	**< 0.0001**
Temperature	2	3615.125	1807.563	57.131	**< 0.0001**
Particle Size*Temperature	6	4597.708	766.285	24.220	**< 0.0001**

Analysis indicated that both variables are significant, and that significant interaction existed between the two variables. The significant interaction between the variables indicates that the relationship between the variables is complex and non-linear, and it hints at the potential for additional unidentified mechanisms at work.

Table 3-9 Particle Size / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95% (Infiltration):

Category	LS means	Standard error	Lower bound (95%)	Upper bound (95%)	Groups*			
Retained by #35	28.083	1.624	24.790	31.376	A			
Passed #270	38.250	1.624	34.957	41.543		B		
Retained by #120	46.000	1.624	42.707	49.293			C	
Retained by #270	59.667	1.624	56.374	62.960				D

**Letters identify statistically distinct groups. All four particles sizes generated statistically distinct infiltration results.*

3.4. Discussion

The laboratory data here confirm our hypothesis that incorporation of ash and char have the potential to induce water repellent behavior in soil through different mechanisms. The incorporation of ash/char created below 350°C presumably creates water repellency through the incorporation of hydrophobic compounds. For mineral ash created at temperatures above 350°C, the effects appear dependent on the particle size of the size the ash. The ability of ash/char to induce persistent effects in soil hydrology is also a significant finding. The soil water repellency created through the volatilization and condensation of hydrophobic compounds generally persists only until the first rain and then may or not return. The data here clearly indicates that water repellent behavior induced by the incorporation of char has the ability to persist in the soil. Furthermore, these effects are less likely to be dependent upon environmental factors such as relative humidity and soil moisture.

The finding that ash depth corresponds to fire intensity, and the observation that ash crust may form in heavily burned areas may seem obvious, but it has management ramifications. Ash crust and induced water repellency create additional hurdles for recovery for the most drastically disturbed soils.

3.5. References

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4. USING RUSLE TO PREDICT MASS WASTING FOLLOWING THE BASTROP FIRE

4.1. Introduction

Effective management of forest soils in the aftermath a large wildfire poses several difficult challenges. During the first few years following a severe wildfire, soil erosion is frequently an ongoing problem. Wildfires increase soil erodibility and run-off by consuming vegetation and soil organic matter (Beschta, Rhodes et al. 2004). Combined, the increased erodibility and runoff lead to increased soil erosion and nutrient loss (LPRT 2011). Losing nutrient-rich topsoil decreases soil fertility and hinders the natural revegetation in burned areas. Soil and ash eroding off the land into water bodies can lead to an increase in the turbidity, nutrient loading, and temperature of water (Keeley 2009). Severe erosion can also lead to filling of reservoirs, deteriorating water quality and quantity, and destruction to infrastructure such as roads, dams and culverts (LPRT 2011). Increased runoff and erosion can shift drainage patterns causing gully and rill formation, and slope failure in hilly terrain. Severe wildfires may also create a water repellent i.e., hydrophobic, layer near the soil surface (Doerr, Shakesby et al. 2000, Letey 2001, Doerr, Shakesby et al. 2006). Water repellent soils have the potential to exacerbate and amply the negative consequences of post-fire erosion.

In steep and hilly terrain, the removal of vegetation and altered soil properties can also lead to mass wasting, further magnifying the total soil erosion. Mass wasting is the downslope movement of soil and weathered material under the influence of gravity.

Shallow soils with low permeability rates on steep slopes are most likely to generate mass wasting in the post-fire environment (Schuster and Highland 2007, Stetler 2014). Mass wasting events have the additional potential to fill or block drainage paths, fill drainage basins, and destroy property (Cannon, Kirkham et al. 2001). In the drastically disturbed post-fire landscape, mass wasting sites are difficult to predict. The ability to identify zones with a high potential for mass wasting would allow forest managers to improve allocation of post-fire recovery resources.

This paper is the product of an effort to evaluate the potential of the Revised Universal Soil Loss Equation as a management tool to predict mass wasting locations in the post-fire environment. Secondly, we sought to incorporate soil water repellency into the RUSLE model in an effort to improve both mass wasting and soil erosion predictions.

4.1.1. RUSLE Used to Predict Mass Wasting

The Revised Universal Soil Loss Equation (RUSLE) is used to estimate soil loss from sheet and rill erosion as a function of five independent factors (Renard, Foster et al. 1991):

$$A = R * K * LS * C * P$$

where A is amount of soil loss in tons/acre/year, R is a measure of rainfall intensity, K is a soil erodibility factor, LS is measure of slope length and steepness, C is cropping and land-cover factor, and P is the conservation practice factor.

Despite the existence of newer and more sophisticated models the RUSLE continues to be widely used because of its simplicity. The data required for the RUSLE is widely available and it is easy to implement in a geographic information system (Miller, Nyhan et al. 2003, Gonzalez-Bonorino and Osterkamp 2004, Larsen and MacDonald 2007, Prasannakumar, Vijith et al. 2012, Fernández and Vega 2016, Ganasri and Ramesh 2016, Gashaw, Tulu et al. 2017, Vijith, Seling et al. 2018).

The use of a GIS-based RUSLE in this setting was not intended to be used to quantitatively predict the soil erosion likely to occur in the park, but rather to identify the zones of highest erosion and most prone to mass wasting. Additional efforts were made to incorporate water repellent soils into the model to further enhance the model's predictive ability.

4.2. Lost Pines Fire and Bastrop State Park

The Lost Pines Forest is a unique 13-mile belt of loblolly pines (*Pinus taeda*) in Bastrop County, Texas. This small isolated belt of pine tree is separated by more than 100 miles from Piney Woods region that covers parts of Texas, Arkansas, Louisiana, and Oklahoma. The Lost Pines is believed to be the remnant of a much larger pine forest that shrank in size during the last glacial period of the Pleistocene era. In addition to the loblolly pine the primary species in Lost Pines Forest are Black Jack Oak (*Quercus marilandica*), Eastern Red Cedar (*Juniperus virginiana*), and Yaupon Holly (*Ilex vomitoria*).

The Lost Pines fire was a major wildfire that struck Bastrop County, Texas, in September and October 2011. The fire was preceded by a year of extreme drought. The area had not received significant rainfall for over a year prior to the fire. Three separate fires started on September 4, 2011, and merged into one large fire that moved south in a progressively widening wedge. The fire occurred following a year of extreme drought. The area had not received significant rainfall in over a year prior to the fire. Strong winds from tropical storm Lee may have contributed to the rapid spread and difficulty fighting the fire. A total of 33,418 acres were burned (LPRT 2011).

Bastrop State Park, as 2000-acre state park located entirely with the burn area was chosen as the study are for this paper. The park topography is hilly, with deep ravines and gullies, and is best known for a large stand of old growth pine trees that survived the fire. Many of negative consequences associated with post-fire erosion were apparent in Bastrop State Park in the years following the fire. In the months following the fire, the park was the focus of recovery efforts, but the work in the park focused primarily on the most visible and frequently visited parts of the park.

Undoubtedly these efforts did prevent some erosion, but mass wasting was a common occurrence on the slopes and hillsides in the first few years following the fire. Erosion led to several road and bridge to failures within the park, and sediment laden runoff eventually caused the failure of a small dam and subsequent draining of a small man-made lake within the park.

4.3. Methods

The data required to create the RUSLE was acquired from several online sources, including a joint report issued by several government agencies following the Bastrop fire (LPRT 2011).

4.3.1. Rainfall Erosivity (R)-Factor

The rainfall factor, R, is a measure of the erosive force of rainfall. It is a function of the volume, intensity and duration of rainfall and can be computed for any given time period but is usually calculated for a given year. Wischmeier (1978) used data from the Western States to develop an empirical formula to calculate R,

$$R = 27.38 * P^{2.17}$$

Where P is the maximum 6 hours rainfall expected to occur within a two-year time span (Wischmeier and Smith 1978). For the purposes of this study, the default value (275) for Austin, TX was used for the entire site (Renard, Foster et al. 1991).

4.3.2. Soil Erodibility (K) Factor

The K factor is an empirical measure of soil erodibility. K-values are determined experimentally, and are primarily determined by soils texture, organic matter, structure, and permeability. Clay soils resist detachment, and thus have a low K-value. With high infiltration rates and easily transported sediment sandy soils have low K-values. Silty soils typically have high K-values because the sediment is easily detached and transported. For the purposes of this study, K-values (Table 4-1) were obtained from Web Soil Survey (Soil Survey Staff 2013). A map of the K-values in shown in Figure 4-1.

Table 4-1 Soils present within Bastrop State Park and related parameters

Soil Series	Soil Texture	K-Factor	T-factor	Area %
Crockett	fine sandy loam	0.43	5	0.60%
Dutek	loamy fine sand	0.17	5	0.30%
Edge	fine sandy loam	0.43	5	26.70%
Jedd	gravelly fine sandy loam	0.28	3	15.60%
Mabank	loam,	0.43	5	0.50%
Padina	fine sand	0.02	5	26.40%
Robco	loamy fine sand	0.2	5	4.30%
Rosanky	fine sandy loam	0.28	5	1.10%
Sayers	fine sandy loam	0.32	5	6.60%
Silstid	loamy fine sand	0.15	5	10.00%
Tabor	fine sandy loam	0.37	5	6.70%
Vernia	very gravelly loamy sand	0.05	5	0.90%
Water		0	0	0.30%

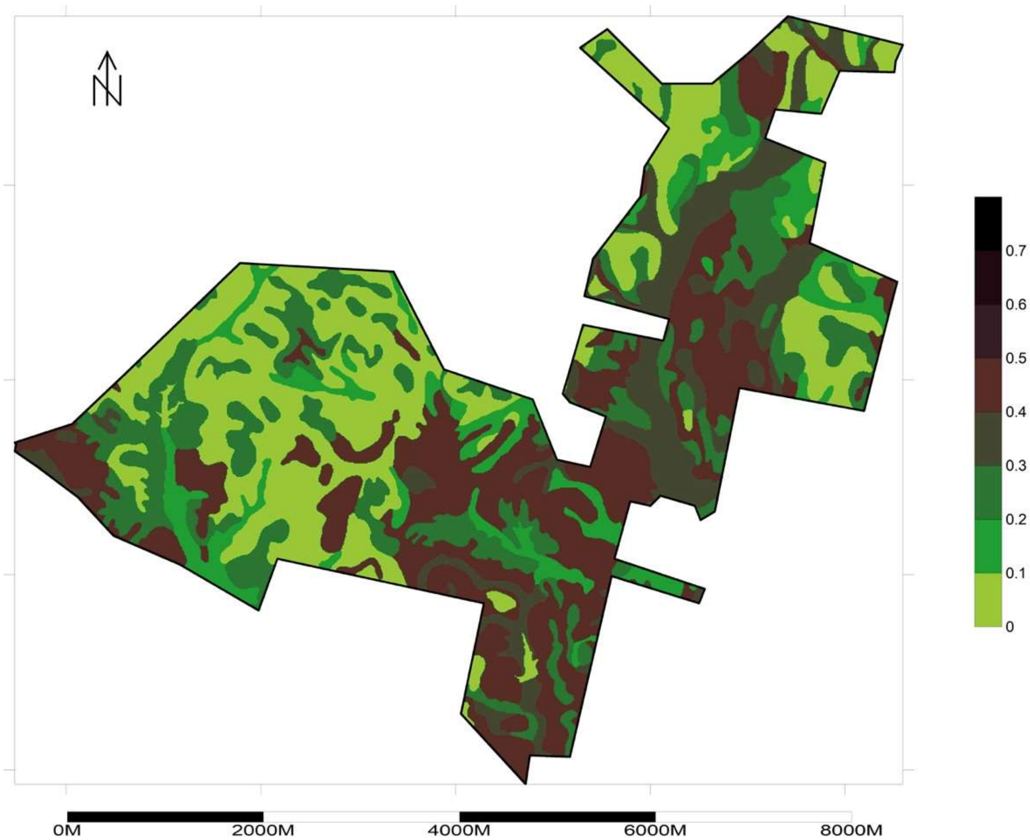

Figure 4-1 Bastrop State Park- Soil Erodibility K-Factor

4.3.2.1. Incorporating Water Repellent Soils

Wischmeier and Smith published a nomograph for determining a soil's K-factor using soil texture, structure, organic matter, and permeability (Wischmeier and Smith 1978, Renard, Foster et al. 1991). As permeability decreases from rapid (>6cm/hr) to very slow (<0.1cm/hr), on the K-factor nomograph, the K-factor value increases by 0.12. The decrease in permeability from rapid to very slow is the most severe case on the nomograph, and fire induced water repellency in Bastrop State Park are unlikely to experience such an extreme shift. However, since the objective of this paper is to assess the use of the RUSLE model to predict mass wasting sites in the post fire environment, 0.12 was added to the K-factor for soils classified as heavily burned in an attempt to incorporate water repellent soils into the RUSLE model (Figure 4-2).. This approach has been used in other studies (Miller, Nyhan et al. 2003, Fernández and Vega 2016, Vijith, Seling et al. 2018).

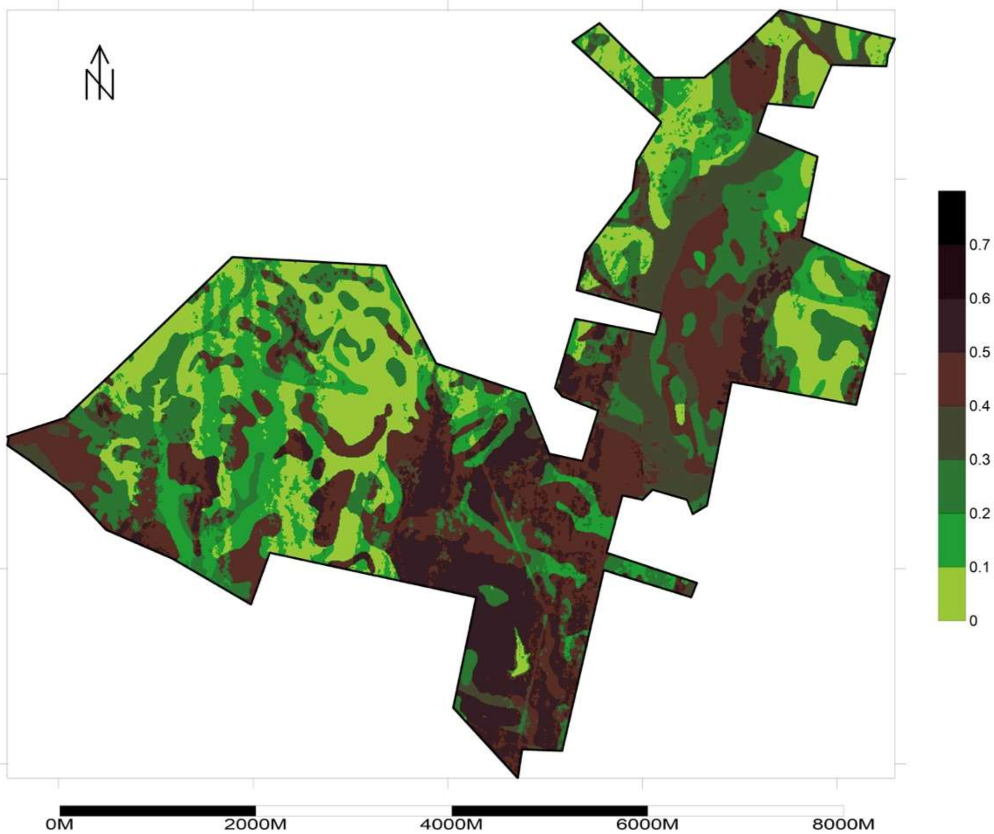

Figure 4-2 Bastrop State Park – Soil Erodibility K-Factor modified for water repellent soils

4.3.3. Slope Length and Steepness (LS) Factor

A USGS 1:24,000 raster DEM (Figure 4-3) was used to calculate the LS factor (Figure 4-4) in Saga-GIS (Conrad, Bechtel et al. 2015) using the method outlined by Moore, (Moore and Wilson 1992). This method allows for the incorporation of complex topography, and accounts for the contribution of upslope areas. The 1:24,000 map scale allows for modeling to be done at a 10m resolution, the minimum resolution required to accurately model complex topography (Miller, Nyhan et al. 2003).

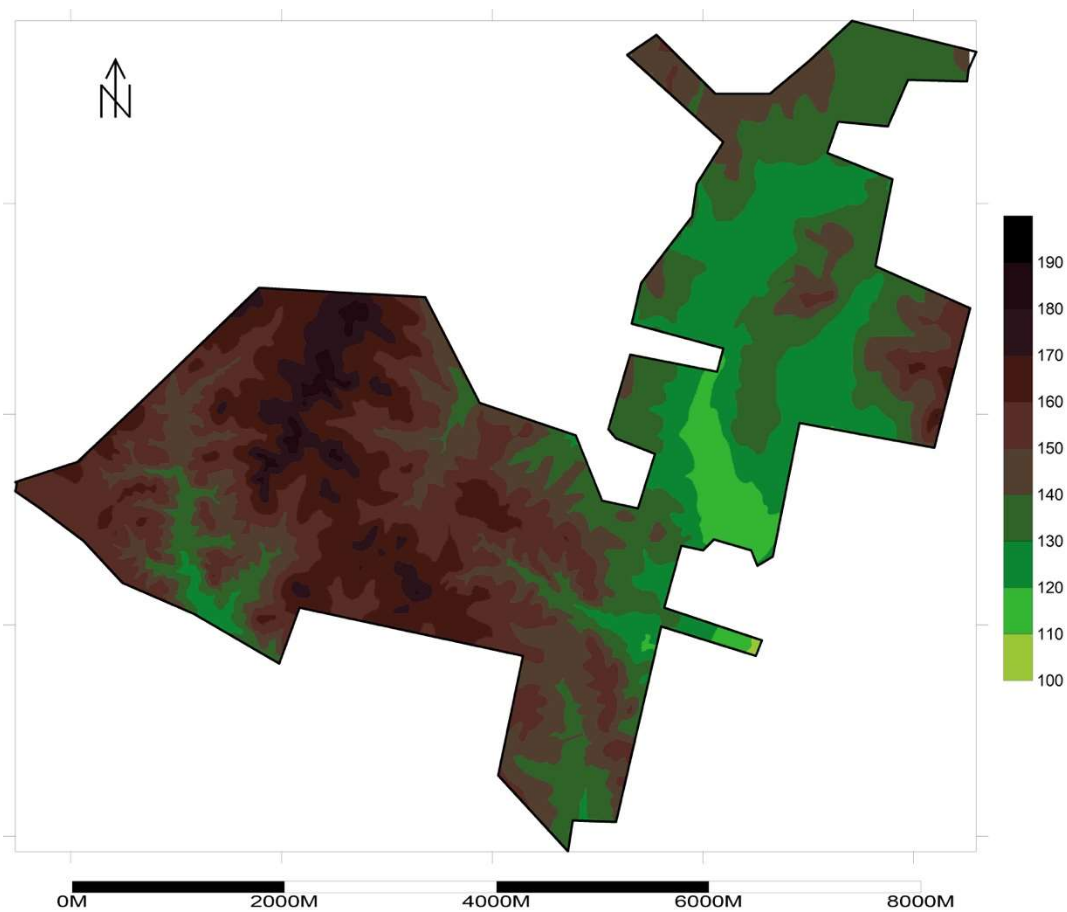

Figure 4-3 Bastrop State Park elevation (meters above sea level)

Figure 4-4 Bastrop State Park Slope Length and Steepness LS- Factor

4.3.4. Cover (C) Factor

Immediately after the fire the Texas Forest Service mapped fire intensity using a combination of remote sensing and ground survey techniques. Areas within the burn area were classified as Scorched, Lightly Burned, Moderately Burned, or Heavily Burned (Figure 4-5) (USDI 2001, LPRT 2011).

The C factor takes into account a series of sub-factors that include prior land use, canopy cover, surface cover and surface roughness (Renard, Foster et al. 1991). For this project, modeling efforts were limited to Bastrop State Park, and nearly the entire park was forested prior to the fire. Parameter values were determined using a combination of values used in other modeling projects and fire intensity descriptions from the post-fire burn mapping (Table 4-2) (Renard, Foster et al. 1991, Karaburun 2010, LPRT 2011, Ganasri and Ramesh 2016).

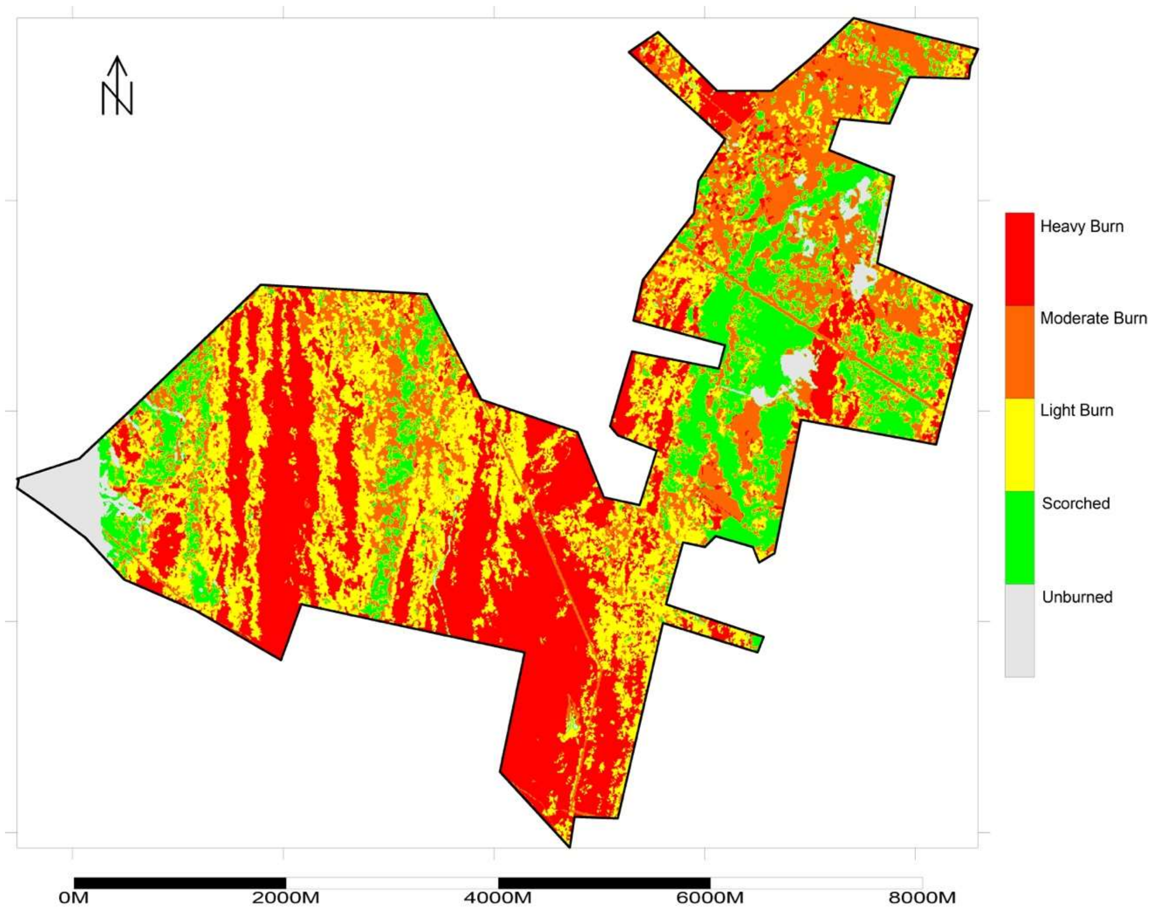

Figure 4-5 Bastrop State Park burn intensity following 2011 wildfire

Table 4-2 – Cover Factor C Values

Burn Severity	% Cover	Soil Condition	C Factor
Unburnt	85		0.004
Scorched	80	Fair	0.05
Light Burn	20	Fair	0.21
Moderate Burn	0	Fair	0.31
Severe Burn	0	Poor	0.45

4.3.5. Conservation Practices (P) Factor

The P-factor takes into account any conservation practices (Renard, Foster et al. 1991). For the purpose of this project, a value of 1.0 was used across the entire project area.

4.3.6. Identifying areas of Mass Wasting

To investigate the RUSLE's ability to predict incidents of mass wasting the geographical coordinates of mass wasting events were recorded while hiking through Bastrop State Park. Due to road and trail damage cause by erosion, parts of park were closed at the time the data was collected. In total 74 mass wasting site were recorded within the accessible parts of the park. No attempt was made to survey the entire park, and it is likely that additional mass wasting sites existed in the inaccessible parts of the park. The model's predicted erosion values at mass wasting sites were compared to the park-wide model predictions.

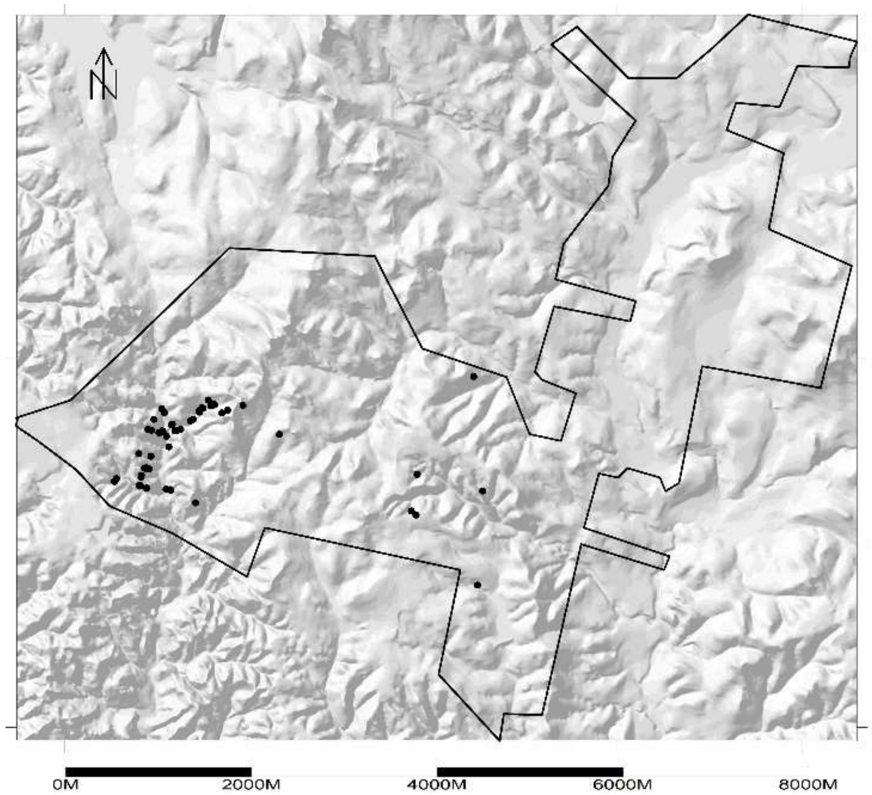

Figure 4-6 – Bastrop State Park mass wasting sites identified in May 2013

4.4. Results

The RUSLE model predicted erosion rates ranging from 0 to 533.72 tons/acre/year (Figure 4-7). When the K-factor was increased to account for water repellent soils, the average erosion rate increased from 12.365 to 16.784 tons/acre/year, but the maximum predicted erosion rate within the park did not change (Figure 4-8).

The mean predicted erosion rate for the 74 mass wasting sites was 45.97 for the simulation with standard K-values and 67.04 for the simulation with modified K-values. The mean predicted erosion of the mass wasting sites had percent rank values of .938 and .947 for the two models, signifying that the mean predicted values for the mass wasting sites were greater than 93.8 and 94.7 percent of predicted values for the entire park.

Figure 4-7 RUSLE predicted soil erosion (tons/acre/year) for Bastrop State Park

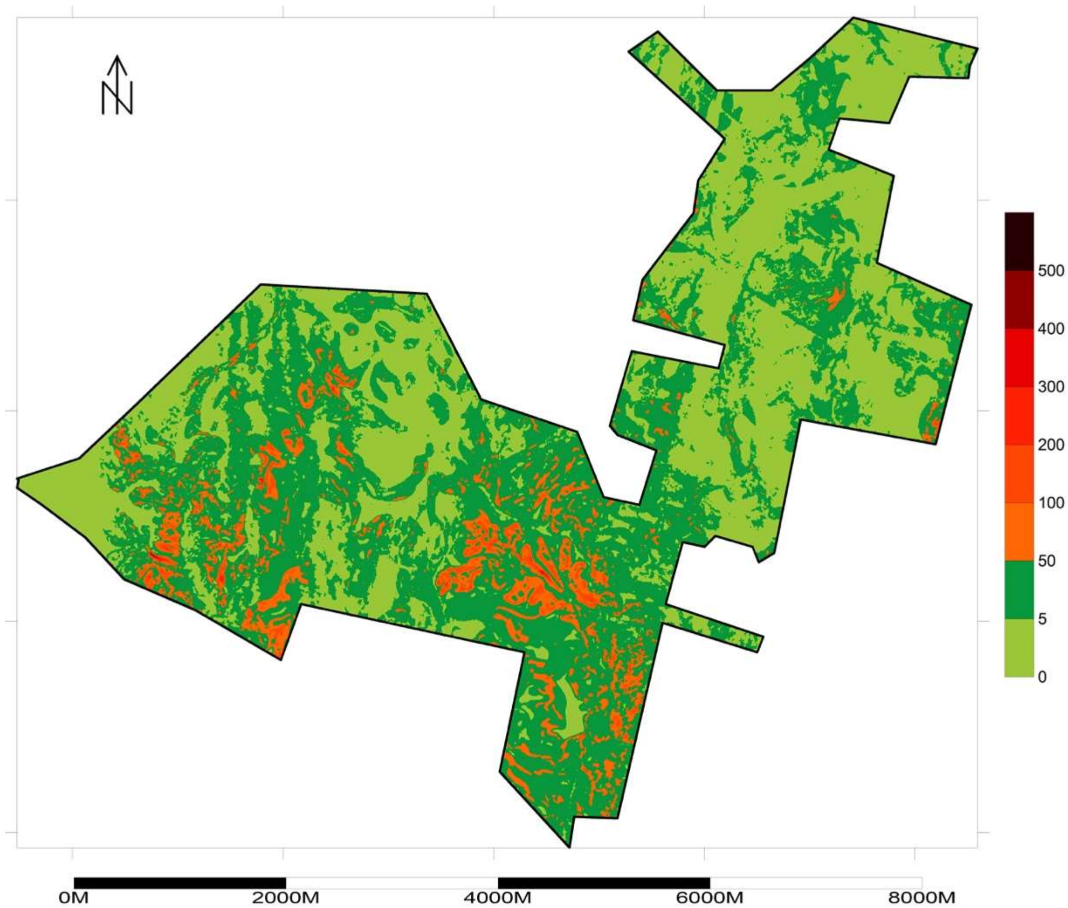

Figure 4-8 RUSLE predicted soil erosion (tons/acre/year) for Bastrop State Park with water repellent soils

4.5. Discussion and Conclusions

Upon examination most of the mass wasting events observed in the park are located within the zones of high predicted erosion. The calculated percent ranks (93.8, and 94.7) confirm this finding. However, the near identical nature of these numbers indicates that the model, at least in this setting, is not particularly sensitive to the soil K-factor. Efforts to incorporate water repellent soils into the model, were essentially superfluous. By comparison the mean calculated LS-factor for the mass wasting sites was 2.05, with a percent rank of 96.5, indicating that the LS-factor alone was a better predictor of mass wasting sites than the RUSLE model. The calculated LS-values range from 0 to 16, but the mean value is only 0.458, and the highest erosion predictions correspond almost exclusively to the extreme LS-values.

Most, but not all of the observed mass wasting sites were located within heavily burned areas, and there does not appear to be any correlation between the mass wasting sited and soil type.

Other studies have had difficulty identifying the effects of fire induced water-repellent soils on landscape scale hydrology (Prosser and Williams 1998, Doerr, Shakesby et al. 2000). At least in this setting, soil erosion and by extension mass wasting, appears to be controlled by the length and steepness of the hillslopes rather than any specific soil property. The formation of water-repellent soils in the post-fire environment is a noteworthy phenomenon, that may control post-fire hydrology on the macroscopic or mesoscale, but there is little evidence that is has the ability to affect long term landscape scale changes in soil hydrology. With that in mind, any efforts to incorporate water repellent soils into large scale erosion models seems unnecessary.

One of the key advantages of a GIS based model is the ability to calculate the LS factor in three dimensions for complex topography, while also accounting for the upslope contributions. The areas with the greatest LS factor values were not always easily identifiable from a simple ground survey. Erosion and mass wasting are different in every post-fire setting. In less hilly terrain, perhaps the relative importance of the K-factor and LS-factor with shift, but at least here, the LS-factor appears to be an excellent tool in identifying areas most at risk for mass wasting.

4.5.1. Texas Forest Service Erosion Predictions

A secondary motivation to implement this RUSLE model was to compare the model predictions to erosion estimates published by the Texas Forest Service in the aftermath of the fire (LPRT 2011). The Texas Forest Service used the RUSLE2 model, but their report omitted important details that would allow others to replicate their work. It is not clear, for example, if they incorporated the actual topography of the burn area into their calculation. Instead it appears that their erosion estimates were done using only typical slope values for individual soil types. Their erosion estimates are also generated assuming bare slopes. This was done to generate a “worst case” scenario, but it ignores the varying fire intensity and vegetative cover after the fire (LPRT 2011).

The Lost Pines report does not present a map of predicted soil erosion. The report however does state that predicted erosion values ranged from 0 to 89 tons/acre/year for the entire burn area. Acceptable erosion rates for most of the soils within the burn area are 5 tons/acre/year (Soil Survey Staff 2013). The report does present a map titled *Water Erosion Potential* (Figure 4-9), and despite their attempt to create a worst-case scenario, 70.2% of the burn area is shown as having low to very low water erosion potential. Notably, only 0.2% is labeled as having a high or very high water erosion potential (LPRT 2011). It is not clear what process they used to set their risk thresholds.

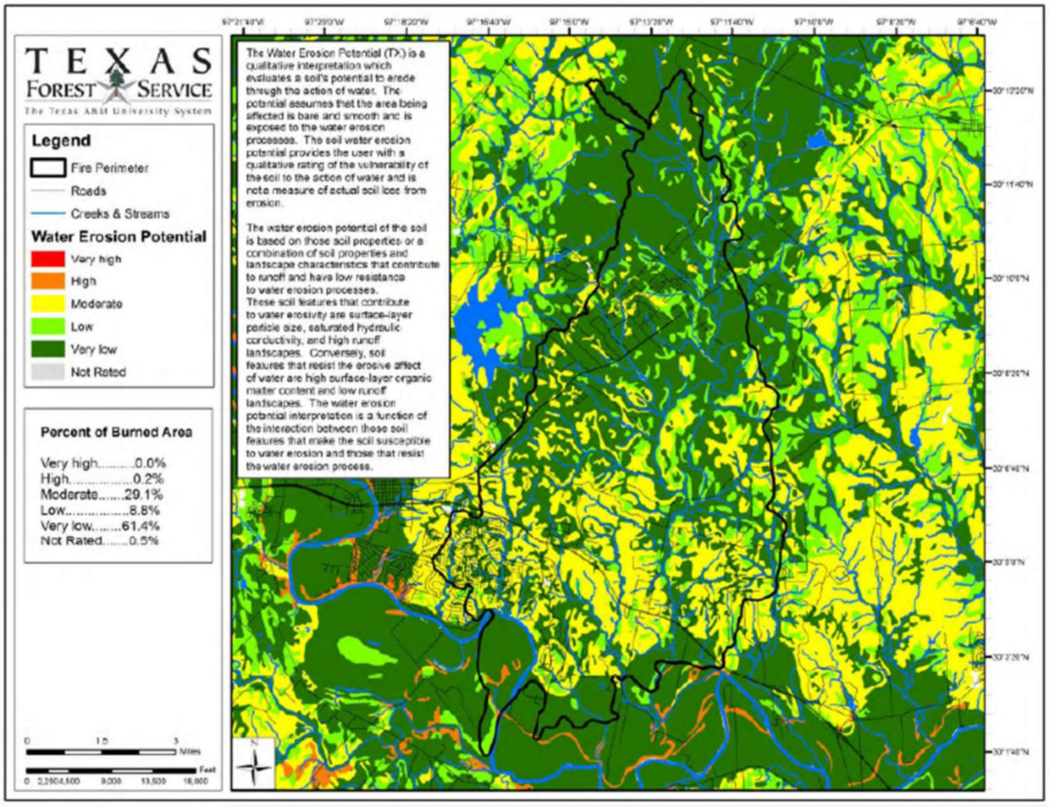

Figure 4-9 Figure S-4 reproduced from Resources Assessment and Response Report -Lost Pines Region (LPRT 2011)

By comparison the study presented here, predicted erosion rates ranged from 0 to 530 tons/acre/year. More than 47% of the park is predicted to have erosion rates in excess of reported T-values, the acceptable erosion rate as specified for the soil series on site. In addition, over 5% of the park is predicted to have erosion rates in excess of 50 tons/acre /year. Some of the discrepancy may be due to the apparent low resolution of the Texas Forest Service modeling. Because the Lost Pines Report does not report actual numbers, it is impossible to directly compare their calculations, but it is fair to say that the erosion that did occur and the associated destruction of park infrastructure exceeded the levels forecast by the Texas Forest Service in their simulations.

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5. CONCLUSIONS

I arrive at the end of this dissertation with a great deal of chagrin. Preparing this document has taken far longer than it should have, and it is only through the aid and extreme patients of my committee members that it has been completed. This project was entirely opportunistic begun within just a few days after the fire. Owing in part to this opportunistic nature, the experiments presented here have some significant flaws. If I had the opportunity to begin this work anew, there are several changes I would make. Still despite the flaws and lengthy period of time that has passed, the findings here are still relevant and noteworthy, and I believe a sound contribution to the body of fire research.

Very few studies have measured the evolution of fire-induced water repellency over time, and charting the changes that occurred over the approximate one year after the fire will hopefully aid in future efforts to better understand the mechanisms at play in the months and years post-fire. The identification of eastern red cedar as the largest contributor to fire-induced water repellency amongst the common woody species found in the Lost Pines region has direct management implications.

In the laboratory we were able to show a very strong correlation between measured SWR and infiltration, but no such correlation was apparent in the field. This is likely because the infiltration measurements done in the field were done after several wet/dry cycles, but it is also likely a case where macroscopic scale laboratory measurements simply do not scale up to field scale properties.

The conclusions I have drawn from my review of the SWR literature and the data I have collected here lead me to believe that the most harmful effects of SWR is its effects on revegetation in the heavily burned areas.

Ash and char have become an area of intense research with in the fire community. At the time of the Lost Pines fire, the development of an ash crust had not been reported anywhere, but it has since been reported by several researchers (I got scooped!) I believe that the data presented here and elsewhere, indicate that while the soil water repellency induced through the incorporation ash and char may be subtler than the SWR induced by volatilization of hydrophobic compounds during a wildfire, it is also likely to have a far greater effect over time due to its persistence in the environment

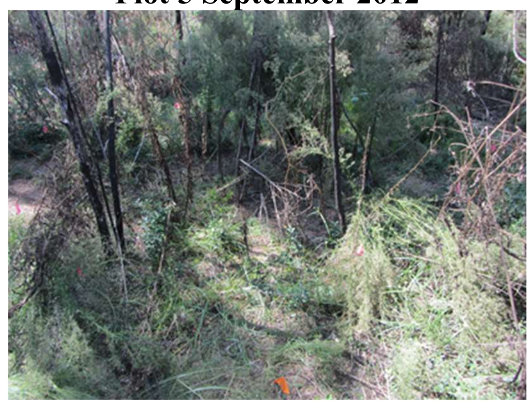
APPENDIX A

Plot 1 -September 2011	**Plot 13 December 2011**
	
Plot 14 March 2012	**Plot 1 September 2012**
	

Plot 2 September 2011	Plot 2 December 2011
	
Plot 2 March 2012	**Plot 2 September 2012**
	

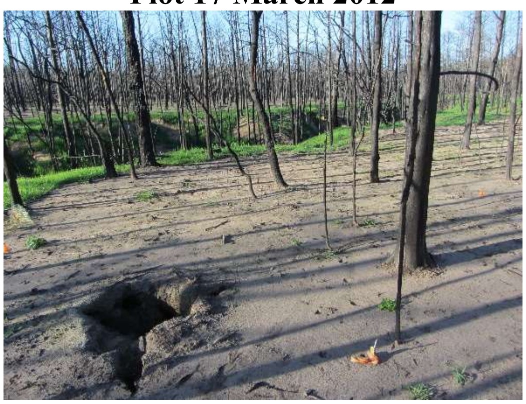
Plot 3 September 2011 	**Plot 3 December 2011** 
Plot 3 March 2012 	**Plot 3 September 2012** 

Plot 4 September 2011	Plot 4 December 2011
	
Plot 4 March 2012	**Plot 4 September 2012**
	

Plot 5 September 2011	Plot 15December 2011
	
Plot 5 March 2012	**Plot 5 September 2012**
	

Plot 6 September 2011	Plot 6 December 2011
	
	Plot 6 September 2012 

Plot 7 September 2011 	**Plot 7 December 2011** 
Plot 16March 2012 	**Plot 7 September 2012** 

Plot 8 September 2011 	**Plot 8 December 2011** 
Plot 17 March 2012 	**Plot 8 September 2012** 

Plot 9 September 2011	Plot 9 December 2011
	
Plot 9 March 2012	**Plot 9 September 2012**
	

Plot 10 September 2011	Plot 11 September 2011
	
Plot 12 September 2011