AN ASSESSMENT OF SOIL WATER REPELLENCY AFTER WILDFIRE IN SOUTHERN BRITISH COLUMBIA: COMPARISON OF METHODOLOGIES AND PREDICTIVE INDICATORS

by

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Abstract

Current studies of soil water repellency show that there are multiple contributing factors to its presence and persistence. Water repellency in soils of the Southern Interior of British Columbia has economic implications, as it can contribute to large scale landslides, and management implications as it affects hydrology and wildfire rehabilitation.

The purposes of these studies were twofold. The first assessed three appropriate methods for testing soil water repellency of burned and unburned soils from eight areas in southern British Columbia. These tests were performed in laboratory conditions as well as *in situ*. The Concentration of Ethanol Drop (CED), Mini-Disk Infiltrometer (MDI) and Spatial Repellency Index (SRI) tests were all used, and the results compared to assess whether all were valid. The studies indicated that the MDI, CED and SRI tests are reliable to detect at least the presence or absence of water repellency in both field and laboratory conditions. The second study assessed whether wildfire would increase the presence and degree of water repellency in the soils one or two years after fire, and whether total organic content, texture and ambient moisture content could be used to predict this soil trait. Wildfire did not increase the presence or degree of water repellency, and soil texture, organic matter content and moisture content were not found to be reliable indicators of soil water repellency in these soils.

This study showed that water repellency exists in burned and unburned forest soils in BC, and that various methods can be used to test for it. Further detailed studies are needed on the predictors on forest soils in British Columbia.

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List of Abbreviations and Acronyms

BC- British Columbia

BEC- Biogeoclimatic Ecosystem Classification

CED- Concentration of Ethanol Drop

CST- Critical Surface Tension

MC- Moisture Content

MDI- Mini-Disk Infiltrometer

MFR- BC Ministry of Forests and Range (now BC Ministry of Forests, Lands, and Natural Resource Operations)

OM- Organic Matter

SRI- Spatial Repellency Index

WDPT- Water Drop Penetration Time

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For Nan

Chapter 1: Introduction to soil water repellency

Wildfire can have evident effects on soils in terms of reduced organic matter, ash creation, and erosion. One of the less obvious impacts of wildfire is on soil hydrology, by altering the flow of water through the soil. One such change in water flow occurs as a result of water repellency of the soil. Letey (2001) defined a water repellent soil as "one on which a drop of water will not spontaneously penetrate".

Soil particles and water are connected in three dimensions by the forces of cohesion (between similar types of molecules) and adhesion (between different types of molecules). Cohesion and adhesion together contribute to *adsorption*, which also plays a role in how water moves through soil. The movement of water also varies according to different potential energy gradients. Gravitational, matric (the grid of soil solids and spaces), and osmotic (ion attraction) potentials power the water flow through porous soil. The direction of water flow is determined by gradients in hydraulic potential (Hanks & Ashcroft, 1980). Flow is from high to low relative potentials.

Repellency has been observed in soils from all over the world, but it tends to develop in areas where organic matter accumulation rates are high, such as humid regions. For instance, Jaramillo *et al.*, (2000) found that the humid Piedras Blancas watershed in Colombia had higher water repellency than the arid Middle Rio Grande Basin in New Mexico attributing this to high rates of organic matter accumulation in humid areas. Repellency is also found in Germany (Buczko & Bens, 2006), Australia (Bond, 1969), Portugal (Leighton-Boyce et al., 2007), Spain (Jordán et al., 2010), South Africa (Scott, 2000), California (Holzhey, 1969; Keeley et al., 2008), Colorado (Lewis et al., 2005; Robichaud, 2000), India, Russia, New Zealand, Florida, Egypt, the Netherlands, Japan, Italy, Scotland, Chile and elsewhere (DeBano & Letey, 1969; DeBano, 1981; Scott, 2000; Wallis & Horne, 1992).

Buczko et al., 2005) researched seasonal variation in water repellency in three different forest types (pure beech, pure pine and mixed stands) in northern Germany. They used the WDPT and CST tests, and water repellency was higher with both tests in the mixed forest stands in the summer. They attribute this to the Mor humus type in these stands, and the higher summer repellency to the dry season.

1.1 What are water repellant soils?

A soil becomes water repellent due to formation of a coating of hydrophobic substances on soil particles. The coating lowers the particle surfaces free energy. Since this is a case of water not being able to pass over these coated surfaces, the term “hydrophobic” or “water repellent” soil is a bit of a misnomer. The term “non-wettable” might be closer to the reality of what is happening in these soils (Bozer et al., 1969; Scott, 2000). These terms will be used interchangeably here.

Water repellency (or “hydrophobicity”) is the state of being non-wettable, where water is partially or wholly restricted from passing over the surface of a particle or material. Soils are not repellent as a whole; rather, individual soil particles and aggregates may resist wetting because of coating by hydrophobic organic compounds (de Jonge et al., 1999). Water repellency is spatially variable and generally most prominent within the top 5- 10cm of the soil profile (Clothier, 2000). Wildfire does not burn through a forest uniformly; hence fire-induced water repellency has very large spatial variability. Lewis et al., (2005) tested soil water repellency against burn severity in the Hayman Fire in Colorado and found that water repellency was highest in moderately intense fires where the soil had an ash cover and relatively high organic matter content.

The measurable soil attributes that are most commonly linked to water repellency are texture and organic matter, but soil water content (Dekker & Ritsema, 1994a), climate, vegetation type, and wildfire have also been shown to influence water repellency. It is important to consider multiple factors of water repellency when attempting to predict it. Studies that consider more than one of these attributes in multivariate models have found higher explanations of variance than studies that consider single attributes alone (Harper et al., 2000).

Doerr et al., (2005) extracted hydrophobic compounds from soils from Australia, Greece, Portugal, the UK and the Netherlands. Their study found that the hydrophobic organic compounds removed from various water repellent soils were generally higher in alkyl C-H groups than the rest of the organic matter. They also found hydrophobic substances in wettable soils, demonstrating that soils have a range of wettability impacted by other factors besides the presence of hydrophobic compounds.

Water repellency changes over time and with several contributing factors. McHale et al., (2007) summarized factors that appear to be related to extremely hydrophobic soils. These include an upper position in the soil profile, drying, oil contamination, soil texture and intense heat from forest fires. Other factors that have been found to affect water repellency in soils are moisture content, higher organic matter content (Lewis et al., 2005) and physical disturbances of the water repellent layer. Letey (2001) points out that the upper layers of soil may be heated to higher temperatures (> 280ºC) than water repellency would be able to form in, but lower, insulated layers that do not exceed temperatures of 280°C or more could be highly repellent.

The effects of fire on soil water repellency are complex and vary from site to site. Fire can have direct effects on repellency by forcing hydrophobic compounds into a layer beneath the soil surface. Hydrophobic compounds could be combusted by high surface temperatures, leaving the surface soil layers wettable. Fire can also have indirect effects by altering soil structure, e.g. reducing porosity, removing organic matter and killing micro/macro organisms that would normally be active in the soil.

1.2 Factors influencing the formation of soil water repellency

1.2.1 Soil texture

Soil texture affects water repellency, with sandier soils generally being more repellent than soils with high amounts of clay (McKissock et al., 2003). Soils with small specific surface areas, such as sands, have fewer bonding sites for hydrophobic substances than soils with larger specific surface areas, such as clays (DeBano, 1981; Harper & Gilkes, 1994; Scott, 2000 and Regalado et al., 2008). This factor is put to practical use in Australia where farmers add clay to sandy soils to ameliorate water repellency (Bond, 1969). Even additions of very small amounts of clay can increase a soil's wettability.

Texture is not always a good predictor of water repellency. Scott (2000) found that the specific surface area of the soil, the sand fraction and the clay fraction were not significant predictor variables of water repellency as measured by various repellency tests on several soils in South Africa. Soils with clay (and higher specific surface area) may be more wettable because there are more sites for hydrophobic compounds to bond in and still have sites for water to bond to the soil particles. de Jonge et al., (1999) also found that particle size alone did not explain the occurrence of water repellency.

Infiltration of water (and air) into soils depends on pore size distribution. Pores occur in a range of sizes and may be classified according to diameter or their hydrodynamic role, for example, how they affect water flow. Bauters et al., (2000) showed that smaller pores in wettable soils filled with water before the larger pores, but in hydrophobic soils, the larger pores filled before the smaller pores.

1.2.2 Organic matter and vegetation type

Dekker et al., (2001) summarized three ways that organic matter induces water repellency in soils. First, the organic matter can dry a certain way that makes it hydrophobic (this is typical with peat moss). Secondly, hydrophobic particulate organic matter can mix with soil particles. Thirdly, residues from decomposing plant, fungi or microbial material such as waxy residues can coat individual mineral soil particles (de Jonge et al., 1999).

The amount and type of organic matter may play critical roles in water repellency, according to Dekker & Ritsema (1994a), Ellerbrock et al., (2005) and Jaramillo et al., (2000). They found that soil wettability increased with soil organic carbon (SOC) content up to a critical SOC content of 10 g/kg. Above 10 g/kg of organic carbon, soil wettability decreased with increasing SOC. They also found that the water content of the organic matter affected water repellency. This is thought to depend on the orientation of hydrophobic and hydrophilic groups and the size of the organic molecules.

Wallis & Horne (1992) took scanning electron micrograph images of sand from wettable and non-wettable soils and observed that the water repellant sand particles were covered with an organic material coating, while the non-repellant sand particles had no coating. They cite Bozer et al., (1969), who hypothesized that there must be a hydrophilic and a hydrophobic end of the coating molecules. The soil particle 'preferentially' bonds to the hydrophilic ends of these molecules, and a hydrophobic bubble forms around the soil particle, much like a soap micelle. The orientation of these molecules on the surface of a soil particle then determines whether or not water is passed along the surface of the particle or not. The orientation is affected by temperature, pH, moisture and physical disturbance.

Bayer & Schaumann (2007) tested water repellency after drying soil samples taken across Germany at different temperatures, and found that heating above 65°C reduced water repellency. This was because the high heat changed the orientation of the hydrophobic organic molecules. DeBano & Letey (1969) tested water repellency at various soil temperatures and found that repellency increased at 175- 200°C and was destroyed above 280°C. Alexis et al., (2010) confirmed that heat from fire does have the potential to destroy organic matter, as they found subsurface temperatures of up to 370°C.

Both fulvic and humic acids have the potential to be hydrophilic. Fulvic acids are soluble in a wider pH range than humic acids, which are deprotonated at only a high pH. The deprotonation increases the polarity and therefore wettability of the molecules. Therefore, higher pH soil solutions may make the soil more wettable (Bayer and Shaumann, 2007).

Some studies, such as those done by Dekker & Ritsema (1994a) and Doerr et al., (2005), found no correlation between organic matter and water repellency. Doerr et al., (2005) determined through various extraction techniques that the major fraction of water repellent organic compounds consisted of polar molecules with hydrophobic portions exposed to the soil solution. Organic matter was only weakly linked to water repellency when using the Critical Surface Tension (CST) test in a study by Scott (2000). He considered the CST test an indicator of the degree of water repellency. The persistence of water repellency had poor correlation to organic matter in Australia (Harper et al 2000), the Netherlands (Dekker & Ritsema, 1994a) and Germany (Buczko & Bens, 2006).

Certain vegetation types on a site increase the soil's water repellency. Scott, (2000) summarizes some plant species that are associated with water repellent soils. These include citrus trees, chaparral vegetation and eucalyptus trees. Bond (1969) found that soil under *Pinus radiata* stands was less repellent than under heath scrub. Soil in the drip/litterfall zone of some trees could have more organic matter or other hydrophobic substance than areas just outside, and will be more repellent (Wallis & Horne, 1992). Clayey portions of the soil may be moist while water repellent sandier areas remain dry because they are less wettable.

Water repellency in soils tends to be caused by plant species with waxy substances in their foliage, such as Eucalyptus species (Leighton-Boyce et al., 2005), chaparral shrub communities (Letey et al., 1962), *phalaris, mallee*, heath and pine (DeBano, 1981). Bond (1969) compared repellency under various vegetation types, and found that soils under grasses had wettable soils within otherwise repellent areas. Holzhey (1969) looked at various vegetation types and found higher water repellency in plant communities with a thicker litter layer, such as the woodland chaparral and the *Pseudotsuga macrocarpa* communities. Certain plant species are particularly capable of enhancing the soil's water repellency. These include citrus trees, chaparral vegetation and eucalyptus trees. Bond (1969) found that soil under *Pinus radiata* stands was less repellent than under heath scrub in Western Australia. Soil in the drip/ litterfall zone of some trees could have more organic matter or other hydrophobic substance than areas just outside, and be more repellent (Wallis & Horne, 1992).

More complex organic structures also affect water repellency in soils. Fungi may create hydrophobic substances that coat soil particles. Biofilms, slimy layers of microbes and their products (generally extracellular polymeric substances or EPS) can coat and connect soil particles (Jones et al., 1969a; Schaumann et al., 2007). Peat can dry out to the point where it is not easy to wet again (Van't Woudt, 1959). Clumps of organic matter can create water repellency even if individual particles are not coated (Dekker et al., 2001).

The amount and type of organic matter and its relationship to soil texture is complex. (Capriel et al., 1995) used diffuse reflectance Fourier transform infrared spectroscopy (DRIFT) to find a significant correlation between coarser soils and alkyl carbon. They suggested that a higher ratio of aliphatic C to total organic C might indicate higher hydrophobicity, at least in their study area in Bavarian Germany. Harper et al., (2000) reviewed studies of water repellency's relationship to soil specific area and organic matter content as well as to soil management in agricultural systems. They found that there is no general formula for predicting water repellency but multivariable regression models explain as much as 63% of the variation in water repellency. This means that multiple factors have to be considered when modeling water repellency. Different tests may also show different results - for example the WDPT test showed no relationship to organic matter, but there was a non-linear relationship with the MED test results and organic matter in a study by Dekker & Ritsema (1994a).

The forest floor can be burned off during fires and the amount of organic matter left after the fire depends on the fire severity and frequency (DeBano et al., 1998). Therefore, knowing the fire regime of a site is important when evaluating soil water repellency in a forest soil as organic matter plays a key role in determining water repellency.

1.2.3 Soil water content

Some soils may be repellent under specific moisture conditions. Drier soils tend to be more repellent (Jaramillo et al., 2000; King, 1981). Dekker et al., (2001) measured water repellency in dune sands at field and laboratory moisture conditions. They measured repellency in the field and then in soils that had been dried at 25º, 65º and 105ºC in the lab, and found a "transitional" water content range of repellency and wettability. The samples that were dried above 105ºC were significantly more water repellent.

Thermal conductivity is partly a function of water content. Heat is transferred relatively slowly in drier soils, because the pore spaces are air-filled, whereas in moist soils, water conducts the heat faster (DeBano et al., 1998). This may insulate the lower soil horizons by dispersing heat in the in the upper, moister layers. This affects the spread of water repellency through the soil as some studies have shown that it can be set along certain temperature gradient boundaries in the soil (DeBano, 2000a).

Moisture conditions are not necessarily a good indicator of soil water repellency. Dekker et al., (2001) measured repellency in dune sands in the field and then again in the laboratory after drying sand samples at 25º, 65º, and 105ºC, and found a range of water contents that showed repellency and wettability. All samples from the 0-2.5 cm soil layer with soil water contents of >23% (vol./vol.), were wettable in the field, but all samples from the same layer with a soil water content of <18% (vol./vol.) ranged from 'slightly' to 'extremely' water repellent. They called the 18-23% soil water content range the 'transition zone" for water repellency occurrence. Deeper in the soil, this transition water content range was much lower, at 2-5% (vol./vol.) for the 16.5 to 19 cm soil layers. Regardless of initial water content the samples that were dried at 105ºC (so that the majority of the soil water evaporated) were significantly more water repellent.

1.2.4 Depth within the soil profile

Upper mineral soil horizons are usually adjacent to the organic horizons; hence water repellent compounds are in close proximity. The depth of the water repellent layer depends on where the hydrophobic compounds settle onto particles. DeBano & Letey (1969) suggest that this is driven by temperature gradients that develop as the soil gets cooler at depth. Top parts of the soil profile are usually exposed to several factors of water repellency formation (temperature change, organic matter, moisture changes etc). This means that surface layers are more likely to be water repellent.

1.2.5 Hydraulic conductivity and soil water repellency

The movement of water through soils is driven by matric, gravitational, and osmotic potentials. The flow of water through soil is not consistent even between similar soils. The infiltration of water into soil depends on pore size distribution and hydraulic conductivity. Hydraulic conductivity is determined by the pore sizes and shapes, particle surface chemistry and roughness, soil texture, and water content.

Soil becomes water repellent (or "non-wettable") with a reduction of hydraulic conductivity at the level of the surface of the soil particles. Particle surface chemistry, porosity, and surface roughness can be affected by soil water content, organic matter content, heating, and weathering (King, 1981). As soil water repellency is affected by so many factors, it is difficult to measure and predict.

1.2.6 Soil heating during fires

It was thought in early studies that soil pores became blocked by ash after fire, and this was the reason for soil hydrophobicity (DeBano, 2000b). Further studies and the use of wetting agents confirmed that this was not quite so simple, and there were some other ways that infiltration was being blocked. Extensive reviews of research on fire's effects on soil water repellency have been conducted by DeBano (2000b), Doerr & Thomas (2000), Letey (2001) Wallis & Horne (1992), and Doerr et al., (2009).

Fire affects organic matter, nutrient ratios, physical structure and other soil properties, and all of their interdependent properties. Fire may drastically affect soil porosity, bulk density, plasticity, elasticity and erodibility (DeBano et al., 1998). Changes range from dehydrogenation of clay particles (although this is unusual because of required temperatures of 460ºC), to collapsed macropores, to rill formation as a result of water repellency.

Two terms describing fire should be mentioned here. Fire intensity is the rate that a fire produces heat, and depends on fuel consumption and rate of spread. Fire intensity is useful to know for fire suppression requirements, but it is not a good indicator of fire temperatures (DeBano et al., 1998). Fire severity is a measure of the total amount of heat given off from a fire, and better describes the effects of fire on different aspects of the ecosystem such as soil or vegetation (DeBano et al., 1998). Fire severity is more relevant than fire intensity when discussing soil heating, because many soil properties seem to be more affected by the total heat applied rather than the rate at which the heat was applied.

Fire is a five-step process. During the pre-ignition phase fuel is heated before it starts to burn (initial ignition temperatures are >325°C).   Then an endothermic reaction called pyrolysis chars the fuel, and drives moisture from fuel surfaces and begins to decompose plant material. Organic compounds are volatilized at this stage. Pyrolysis leads into and continues throughout the next stage, called flaming or combustion. This is an exothermic reaction where aboveground temperatures may reach 1,400°C, although only 10-15% of the heat released is transmitted downward. The heat produced during combustion can speed up the drying of fuel ahead of the burning front. Flames may not necessarily occur, as some organic material such as peat or thick duff layers may just smolder. This leads us to the next stage, called smoldering. Finally the combustion stops due to lack of fuel, oxygen or heat, and the fire eventually dies out (DeBano et al., 1998).

DeBano (2000b) postulated that the steep temperature gradient that develops during severe fires would push hydrophobic substances deeper into the soil. Organic hydrophobic substances repel water from the surface of unburned soils. Heat from fire vaporizes these substances and they are drawn further down into the soil profile along a steep temperature gradient, where they distill onto soil surfaces. This creates a water repellent layer at some depth, on a parallel plane to the soil's surface, and with an overlying horizon of wettable soil (DeBano & Conrad, 1978).

The magnitude of changes to soil depends on many factors including fire interval, intensity, and severity. A low severity fire which just burns the surface litter may not heat the soil at all; however, a high severity fire which burns for a long period of time may heat the mineral soil to more than 600ºC (DeBano et al., 1998). Generally, only the upper 2-3 cm of the soil is subjected to extremely high temperatures. Heat is transferred through the soil primarily by radiation, convection, and conduction, but also through mass transport, vaporization, and condensation (DeBano et al., 1998). Soil may be insulated from the heat of the fire by the litter (or "duff") layer if it does not combust.

Soil water content is positively related to thermal conductivity. Heat is transferred relatively slowly in drier soils, because the pore spaces are air-filled, whereas in wet soils, water conducts the heat faster (DeBano et al., 1998). Dry soil at the surface may insulate the lower soil horizons by confining the heat in the upper layers. Aside from this insulation by the surface, the heat in the lower layers will be lessened because the heat energy is dissipated at the surface.

Different soil properties such as organic matter content, nutrient ratios and physical structure may have different sensitivities to heat. Soil biology is affected as well. For example, small mammals, seeds, plant roots, and fungi are extremely vulnerable to heat, since they are usually located at or close to the soil surface, and they can be killed with relatively mild heating. Temperatures of 60ºC will coagulate proteins (Precht & Chrisphersen, 1973), 100ºC will kill most living organisms, 220ºC will completely dehydrate soil, 220º- 460ºC will combust organic matter, and 460ºC will drive off hydroxyl (OH) groups from clay particles, affecting carbohydrate structures as well as pH (DeBano et al., 1998). Elements such as manganese and calcium are relatively insensitive to heat, as their melting points are >800ºC. Typical forest fires in western North America reach maximum subsurface temperatures of about 300ºC (DeBano et al., 1998), so the elements in the soil solution should not be affected by the heat.

1.2.7 Effects of fire on soil structure

Fire may drastically affect soil porosity, bulk density, plasticity, elasticity, and erodibility (DeBano et al., 1998). Changes range from dehydrogenation of clay particles (although this is unusual because of required temperatures of 460ºC), to collapsed macropores, to rill formation. Micro and macro organisms that normally mix the soil can be killed during fires. Since organic matter binds inorganic particles together, the soil aggregates collapse and fine particles can plug air spaces when the organic matter is burned off (Kutilek & Nielsen, 1994). This decreases porosity and infiltrability.

A hillside that has experienced a slide arguably has the most visible change in soil structure, however there can be structural changes on a much smaller scale. If the hydrophobic layer is beneath wettable surface layers (Krammes & DeBano, 1965) in (DeBano, 2000a), the wettable soil can become saturated if there is inadequate lateral drainage. Then the pore pressure builds up and can break apart the wettable and repellent layers. This shearing may result in rill formation or even debris flow on top of the water repellent layer, depending on the slope, soil horizons and water content.

Raindrop splash also causes erosion on bare soil as droplets hit exposed layers and displace the surface particles. It might affect hydrophobic soils to a greater degree than wettable soils, because particles remain dry and non-cohesive, so are easily pushed out of place by the raindrops. The impact of the drops can cause compaction and even sealing of the remaining pores by displaced particles (DeBano et al., 1998).

1.3 Effects of water repellency on post-fire water and soil movement

A burned soil that is water repellent will usually have a wettable layer on top of the non-wettable soil, because ash on the surface is wettable and the hydrophobic organic compounds are forced deeper into the soil because of a temperature and concentration gradient (DeBano, 1981). An example of large mass-movement, where the suspected trigger was water repellency in lower soil layers, occurred in the Kuskonook Creek area north of Creston, British Columbia (BC), in August 2004. The resulting slide destroyed two homes, but fortunately no lives were lost.

Debris flows can cause much larger sediment loads than are expected by typical hydrological calculations. The sediment fills drainage structures, causing them to overflow, and exposes people and structures downstream to flooding and mud or rockflows. The wildfires around the lakeside neighborhoods south of Kelowna, BC in 2003 resulted in flooding and damage of several homes downhill from the burned slopes.

1.4 Financial implications of post-fire water repellency

In the summer of 2003, almost 2,500 separate fires totaling 265,000 ha were reported to the BC Ministry of Forests and Range (MFR). This was more than twice the number of fires than in any other province, and 500 more fires than the previous 10 year average. In 2003, suppression costs alone were over $375 million (Filmon, 2004).

There were several fires in 2003 and 2004 in BC that had massive erosion events subsequent to the wildfires. Of these, the Okanagan Mountain Park and Vaseaux Lake fires in the Okanagan and Kuskonook fire in the east Kootenays had mass movement of debris that caused damage to private and public property. This erosion added expense to already costly fire seasons. For example, after one extreme rain event on hydrophobic soils after the 2003 Okanagan Mountain Park fire near Kelowna, BC debris flow damage to personal property, roads, and drainage structures amounted to approximately $1 million in damage (D. Dobson, Dobson Engineering, personal communication). An additional $2 million was spent by the City of Kelowna in 2004 on improving the drainage structures after the debris flows.

1.5 Techniques and methods used to measure repellency

Repellency is not a simple property to measure since it has tremendous variability in all dimensions in the soil (Dekker & Ritsema, 1994b). Soil that is repellent at one spot may be completely wettable 2 cm away. There is no single, universal measure for a water repellent soil. Instead, a variety of properties are measured to indicate the presence and degree of repellency. These measurements follow the principles of two different approaches: advancing contact angle or water drop penetration time.

1.5.1 Contact angle

The solid-liquid contact angle, or the angle between a drop of liquid and a solid at the advancing edge of the liquid, is an indicator of the wettability of a surface. As the liquid moves over the surface of the solid, it displaces gas until the spreading stops. This advancing contact angle (ACA) is measured by its free energy of the solid-gas interface (Roy & McGill, 2002; Bachmann et al., 2003). This free energy cannot be directly measured, so thermodynamic indicators of the free energy are measured instead (e.g. (Douglas et al., 2007) The ACA is affected by the surface of the solid and by the surface tension of the liquid. A liquid with low surface tension will spread out over the solid, making a smaller contact angle than a liquid with higher surface tension. Water with a high concentration of solutes (electrolytes), with its lower vapor pressure, will have lower surface tension and will wet a surface more readily than pure water.

Smaller contact angles mean that the surface is more wettable than if the contact angles are larger (Figure 1-1). Wettable soils have an ACA of 0-90° and water repellent soils have an ACA >90° (Roy & McGill, 2002). A completely non-wettable surface would have an ACA of 180° (Hillel, 1971). The ACA is assumed to be 0° (and, therefore, the soil to be totally wettable) in most soils analyses. The ACA is affected by the surface texture of the solid, chemistry and surface tension of the liquid, gas adsorption, and the length of time of contact.

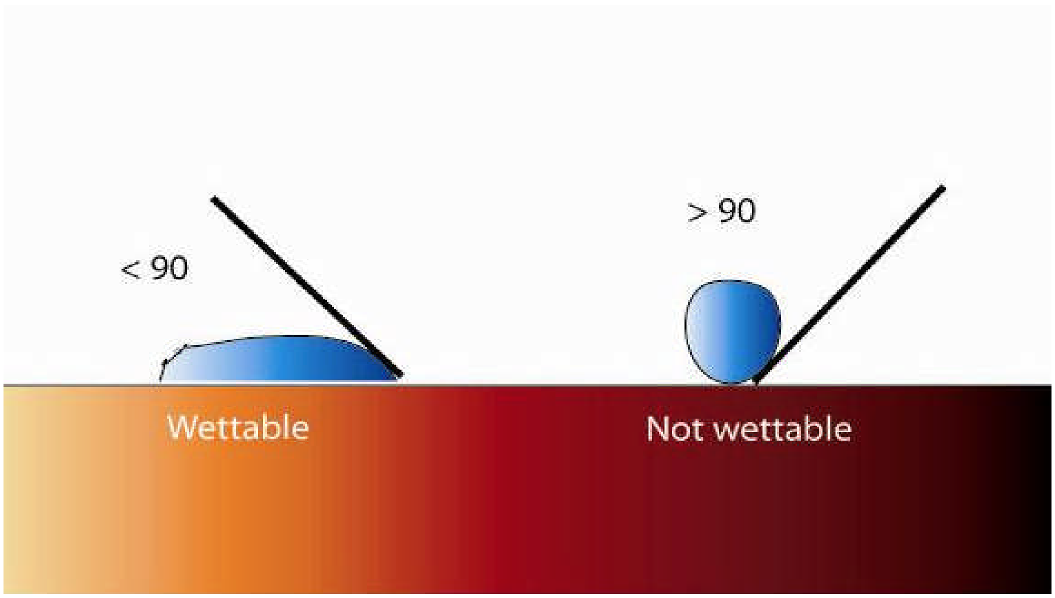


Figure 1-1: Advancing contact angle

In 1805, Young published a paper on the contact angle of water moving through soil as an indicator of the free energy of the three interfaces. He formulated the following equation (from Roy & McGill, 2002):

$$\text{Cos}\ \theta = \frac{\gamma SG - \gamma SL}{\gamma\ LG} \qquad \text{(Eq. 2)}$$

Where: θ is the contact angle (°)

γSG is the free energy of the solid-gas interface (J/m^2)

$\gamma\ SL$ is the free energy of the solid-liquid interface (J/m^2)

$\gamma\ LG$ is the free energy of the liquid-gas interface (J/m^2)

The numerator is the energy released in forming a unit area of solid-liquid interface.

The solid surface texture is assumed to be smooth in most calculations, due to the difficulty of identifying the texture itself. The surface tension, however, changes with the concentration of solutes in the liquid. Surface tension results from the unbalanced attraction (cohesion) of the molecules of the liquid, and between the liquid and gaseous molecules at the liquid-gas interface (Brady & Weil, 2002). If this is smaller than the adhesion between the liquid and the solid and the solid and the gas, the liquid will wet the surface of the solid. The contact angle here would be less than 90°.

The method of measuring the contact angle can be estimated from a simple test, called the Molarity of Ethanol Drop ('MED', an adaptation of the Critical Surface Tension) test, or measured with a Capillary Rise test (Bachmann et al., 2003).

The MED test measures the initial severity of water repellency (Douglas et al., 2007). It uses increasing concentrations of ethanol to measure the lowest concentration that does not bead on the soil surface, hence the alternative name Critical Surface Tension test. As ethanol concentration increases, the surface tension decreases to an asymptotic level. Roy & McGill (2002) describe the method in laboratory conditions, where a testing dish of smoothed, dried, sieved material is subjected to individual drops of the ethanol from lowest to highest concentration. Droplet absorption is timed from when the drop touches the soil, and stops as soon as the drop starts to enter the soil. If the drop does not absorb within a set time (1, 5, or 10 s), the next highest molarity of ethanol is tested.

There are several capillary rise methods that use contact angles to determine the severity of water repellency. Note that *capillarity,* or *capillary action* is defined as the distortion of the boundary of a liquid when it comes into contact with a solid. It is caused by adhesion of the water molecules to the soil particles and the surface tension of the water (Brady & Weil, 2002).

One way to measure the contact angle is to use a precision tensiometer to determine the rate of weight gain of the soil as it is exposed to a reference liquid (either hexane or water)

(Bachmann et al., 2003; Roy & McGill, 2002). This method requires samples to have the same bulk density, which adds some complication to the process (Ellerbrock et al., 2005).

Modified capillary rise methods developed by Bachmann et al., (2003) for measuring contact angles are the Wilhelmy plate method (WPM) and the Modified Capillary Rise Method (MCRM). The WPM involves dipping a soil coated glass plate into a test liquid. The soil is stuck to the plate with double-sided tape. The glass plates are attached to a balance and then the contact angle is measured with a precision tensiometer after removing the plate from the liquid, and analyzed to determine the specific contact angle between 0° and 180°. The MCRM is used for soils that have contact angles > 90° and uses test liquids of various alcohol concentrations.

These methods can be used to measure repellency in laboratory conditions or *in situ*. A disadvantage of these methods is that they require more sophisticated equipment and greater knowledge of soil physics than some other methods.

1.5.2 Water Drop Penetration Time

Water Drop Penetration Time (WDPT) is a proxy for the persistence of water repellency (Dekker et al., 1999). The time needed for a water droplet to enter the soil surface is measured (e.g. Henderson & Golding, 1983; Scott, 2000). Bachmann et al., (2003) describe this test as an indirect measure of the surface energy, or ”energy required to form an additional unit area of new surface at the interface.”

Dekker et al., (2001) and Robichaud & Hungerford (2000) used the WDPT at various depths, starting with the organic surface, then the top of the mineral soil, and continuing down at 1, 2, 3, 5, and 7 cm depths. Twenty drops were placed randomly on each layer and timed for absorption, for up to 180 s. If the drop was absorbed within 0-5 s, the soil was not water repellent; within 5-60 s it was slightly repellent, within 60-180 s it was moderately repellent, and above 180 s it was extremely repellent. Dekker & Ritsema (1994a) used the same system but with 5 hours being the lower limit for an extremely water repellent soil.

Jaramillo et al., (2000) used a scale of 0-10 s (wettable), 10-90 s (slightly repellent), and above 90 s (strongly repellent). They timed three drops of distilled water on a smoothed surface of a soil sample. They tested the water repellency of the same soils both *in situ* (for "actual" water repellency at field moisture conditions) and after drying in the laboratory (for "potential" water repellency) at 40°C for several days.

An adaptation of the water drop penetration time used in the studies presented in this thesis uses a Mini-Disk Infiltrometer (MDI) from Decagon Devices. Mini-Disk Infiltrometers are compact infiltrometers with a porous steel disc at the base, and an adjustable suction tube in a separate chamber at the top. The cylinders are marked like graduated cylinders so that the volume of water sucked out the bottom of the cylinder can be viewed. It is intended to measure the hydraulic conductivity of the soil, and is easy to use at many sites in the field because of the simplified apparatus used (Decagon Devices, 2011). Lewis et al., (2005) also used this tool to assess soil water repellency after the Hayman fire in Colorado in 2002.

The WDPT test is useful in determining presence/absence of repellency, but is somewhat cumbersome for determining exact degree of repellency, as observing a water droplet for hours is impractical and there can eventually be losses to evaporation.

1.6 Objectives

At the time of the planning stages of this project, only two peer-reviewed, published works on water repellency in BC existed. Henderson & Golding (1983) studied water repellency persistence after prescribed burning in two Greater Vancouver (coastal) municipal watersheds. They used the WDPT method and did not find any difference between burned and unburned soils. Barrett & Slaymaker (1989) also used the WDPT test at six unburned sites throughout southern BC and found water repellent soils at all subalpine sites that had evidence of organic matter accumulation. Recent fires in the southern interior of BC have had substantial costs associated with post-fire erosion of soils that are believed to be water repellent. There was concurrent work on soil water repellency after fire by Curran et al. (2006). Further work is needed to establish the indicators and predictors of water repellency in the region in order to aid decisions about fire rehabilitation and watershed structural preparations such as culvert expansion. My study represents an exploratory assessment of water repellency across a wide physiographic range of BC to give future researchers information on where repellency may exist.

The objectives of this study were twofold and are presented in separate chapters of the thesis. The first objective was to compare simplified testing methodologies for the Molarity of Ethanol Drop (e.g. Critical Surface Tension) and Water Drop Penetration Time test, which are described in Chapter 2. The second objective, described in Chapter 3, was to test for indicators that could predict the occurrence of water repellency after wildfires in southern British Columbia. Tests and predictors were kept as simple, cheap and user-friendly as possible in order to be useful for field users interested in assessing the post-fire risk of flooding and erosion. Results from this study could be used to augment forest fire risk assessments and site rehabilitation tools.

Hypotheses associated with the first study objective were that various methods of testing for soil water repellency would show similar results for soils from the same sites:

1. Modified Molarity of Ethanol Drop tests (Concentration of Ethanol Drop or CED tests) will show similar ranges of results in the field as in the lab.
2. Field Mini-Disk Infiltrometer (MDI) tests will show similar ranges of results in the field as in the lab.
3. Field CED and field MDI tests will show similar patterns of results for the same sites.
4. Laboratory CED and laboratory MDI tests will show similar patterns of results for the same sites.
5. A modified Water Drop Penetration Test (also called the Spatial Repellency Index) in the field will show the same trends of water repellency as the CED and MDI tests.

Hypotheses associated with the second study objective were that environmental factors and conditions that have been found to affect water repellency in similar studies in other regions could be used to predict the presence of post-fire water repellency in BC:

6. Wildfire that burns the litter layer and fine tree branches will increase the existence of water repellency in soils.
7. Greater organic matter content in the soil will increase the degree of water repellency in all tests used.
8. Drier soils will have higher instances of water repellency.
9. Soils with greater specific surface area measurements will have lower incidence of water repellency in all tests.

Chapter 2: Comparing water repellency tests for forest soils in southern British Columbia

2.1 Introduction

Soil water repellency (i.e. hydrophobicity, or non-wettability) is a soil property that describes the ability of the soil particles to be wetted. There is no unit to water repellency, and there is no single absolute measurement for a water repellent soil. Instead, a variety of properties are used to indicate the presence and degree of repellency, and indicators are measured as proxies for water repellency.

Water repellency is determined either in general physical chemistry or soil science (McHale et al., 2007). Physical chemistry tests of water repellency tend to be focused around precise solid-liquid contact angle measurements (Bachmann et al., 2000), while soil science tests tend to be more field-friendly, with simplified equipment, and they determine the presence or degree of water repellency compared across a number of soils or sites. The most common tests for soil science purposes are the water drop penetration time (WDPT) and Molarity of Ethanol Drop (MED) (Bachmann et al., 2003; Dekker et al., 1999; Doerr et al., 2006; Van't Woudt, 1959).

Douglas et al., (2007) compared the WDPT and MED tests to determine factors in soil water repellency persistence and initial severity, and correlations between the two tests. The difference between the surface tension of the droplet solution and the critical surface tension of the soil had a linear free energy relationship with the WDPT tests. Buczko & Bens (2006) compared water repellency measured with the WDPT and contact angle tests and found that there was low correlation between the two. They attributed the differences to the possibility that contact angle takes time to measure after the solution is dropped on the soil, and the WDPT starts as soon as the solution is placed on the soil.

Lewis et al., (2005) compared the WDPT and MDI tests and assessed whether burn severity and water repellency were correlated at the Hayman Fire in Colorado. The MDI test was actually analyzed two ways with 5 mm tension in the tension chamber- MDI_{time} and MDI_{rate}. The first amount, $MDI_{time,,}$ measured the time between contact with the soil and the rise of the first air bubble in the tube. MDI_{rate} measured the volume of water that infiltrated into the soil in the first minute after contact. Both measures can be used to indicate relative water repellency at the soil surface. The WDPT test measured the length of time that a drop of water remained on the soil surface, up to a maximum of 300 s. In their study, the WDPT and MDI tests had an overall correlation of -0.64 ($p < 0.0001$).

There is limited published data on water repellency comparisons between laboratory and field tests (Doerr et al., 2009). Tillman et al., (1989) examined repellency on pure sand and concluded that soils that were repellent in the field and dried, shaken and sieved for laboratory preparation had their repellency removed; however, incubation restored the repellency.

The purpose of this study was to compare simplified testing methodologies for the Molarity of Ethanol Drop (e.g. Critical Surface Tension) and Water Drop Penetration Time tests both *in situ* and under laboratory conditions. This will allow us to determine whether comparisons of water repellency using various techniques and before and after handling for laboratory tests are valid.

Hypotheses associated with this study objective were that various methods of testing for soil water repellency would show similar results for soils from the same sites:

1. Modified Molarity of Ethanol Drop tests (Concentration of Ethanol Drop or CED tests) will show similar ranges of results in the field as in the lab.
2. Field Mini-Disk Infiltrometer (MDI) tests will show similar ranges of results in the field as in the lab.
3. Field CED and field MDI tests will show similar patterns of results for the same sites.
4. Laboratory CED and laboratory MDI tests will show similar patterns of results for the same sites.

5. A modified Water Drop Penetration Test (also called the Spatial Repellency Index) in the field will show the same trends of water repellency as the CED and MDI tests.

2.2 Materials and methods

2.2.1 Study sites

Soil samples were taken from eight areas in southern BC that had been burned by wildfires. The areas were selected between the Coastal Mountains to the west and the Rocky Mountains to the east, and the US border to the south and to the town of Barriere to the North. These fire sites were chosen for this study based on the following criteria: (1) relatively large size (>1,500ha), (2) experienced a wildfire in 2003 or 2004, (3) good access due to a network of roads, and (4) observation of soils exhibiting hydrophobicity (for example, a Forest Practices Board report from February 2005 identified Cedar Hills, Kuskonook and Lamb Creek as having hydrophobic soils that caused debris flows after the wildfire).

The study locations (Figure 2-1) were:

1. Okanagan Mountain Park (southeast of Kelowna),
2. Vaseux Lake (near Okanagan Falls),
3. Town Creek (just north of Lillooet),
4. Lamb Creek (south of Cranbrook),
5. Kuskonook (north of Creston),
6. Cedar Hills (outside of Falkland),
7. Barriere/McLure (around Barriere), and
8. Vermelin (north of North Barriere Lake).

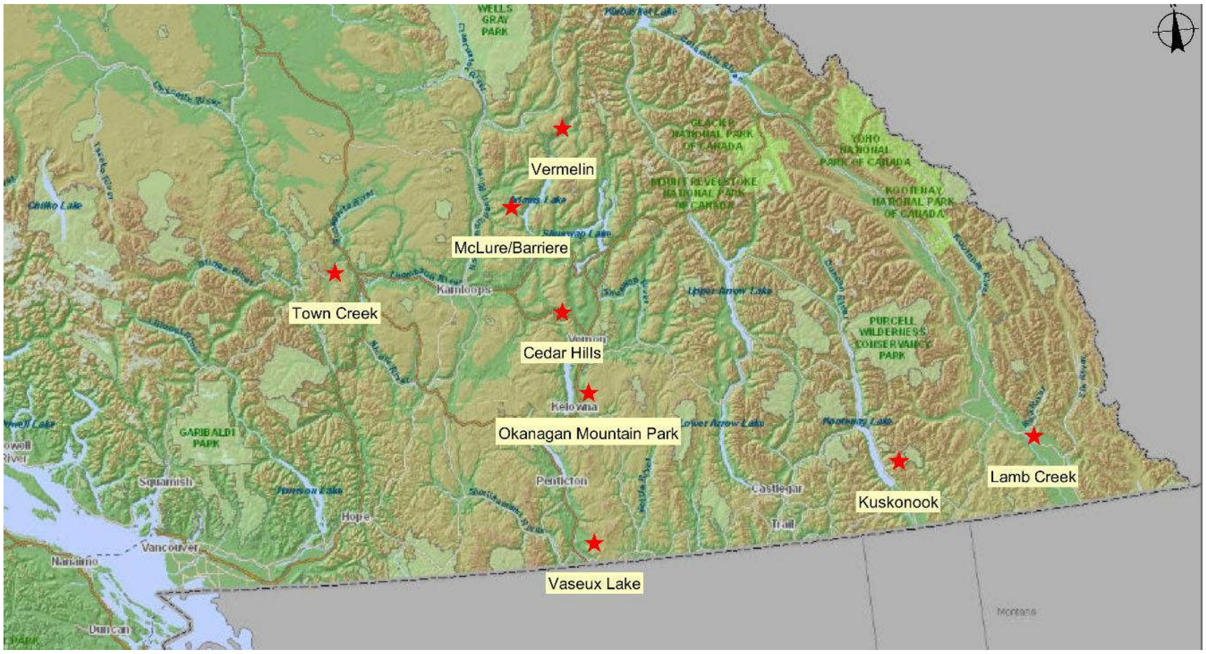


Figure 2-1: Study areas in southern British Columbia

Specific BEC zone, subzone, elevation range, soil type, soil texture and maximum July temperature are outlined for each study area in table 2.1. Note that these were not used to stratify the plots during the design of these studies; rather, the data are presented for descriptive purposes. **Appendix A** describes more information on each wildfire, including available weather data.

Table 2-1: Site and soil characteristics of the fire areas included in this study

Fire site	Area #	BEC Zone	1° Forest cover	Aspect (degrees)	Average elevation (masl)	Slope	Max. mean July Temp. (1971-2000)[4]	Soil type[5]	Average Soil Specific Surface Area (m^2/g)	Average soil moisture content (%)		Average soil total organic matter (%)	
										Burned	unburned	Burned	unburned
McLure/ Barriere	1	MSdm	Pl/S	88	1,241	17	21.7	Humo-Ferric Podzols/ Gray Luvisols	165	15	26	5	8
	2	IDFmw/xh	Fd	251	954	19	23.8		118	28	27	12	6
	3	ICHmk/ IDFmw	E	122	985	17	22.9		124	24	26	10	6
Town Creek	1	MSxk	Pl	218	1,417	15	21.8	Dystric and Eutric Brunisols	150	15	36	10	11
	2	IDFdc	Fd/Pl	167	1,389	35	22		137	7	14	10	11
	3	IDFdc	Fd/Fd	133	1,179	23.5	22.8		108	20	31	11	11
Lamb Creek	1	ESSFdm	Pl	182	1,642	15	18.8	Orthic Humo-Ferric Podzols	76	13	25	11	10
	2	ESSFdk	Pl	100	1,948	13	19.4		142	24	33	8	14
	3	ESSFdk	Pl	45	1,652	15	20.2		135	31	30	9	10
Kuskonook	1	ESSFdmw	Pl	228	2,014	17	18.7	Humo-Ferric Podzols & Orthic Dystric Brunisols	80	4	15	9	16
	2	ESSFdmw	B	185	2,020	15	19.1		71	7	10	9	9
	3	ESSFdm	Pl	240	1,807	28	19.2		55	7	17	6	9
Cedar Hills	1	IDFmw	Fd	226	1,183	17	22	Humo-Ferric Podzols	83	11	16	6	11
	2	IDFmw	At/C	169	878	17	23.7		123	9	8	4	10
	3	IDFmw	At	155	922	4	23.3		104	18	6	5	8
Vermelin	1	ESSFwc	Sx	188	1,603	20	19	Humo-Ferric Podzols	81	8	22	5	6
	2	ESSFwc	Ac/Sx	249	1,541	14	19.3		90	18	23	4	5
	3	ICHdw	Fd/Pl	146	659	25	23.5		55	5	18	5	7

Fire site	Area #	BEC Zone	1° Forest cover	Aspect (degrees)	Average elevation (masl)	Slope	Max. mean July Temp. (1971-2000)[4]	Soil type[5]	Average Soil Specific Surface Area (m^2/g)	Average soil moisture content (%)		Average soil total organic matter (%)	
										Burned	unburned	Burned	unburned
Okanagan Mountain Park	1	IDFxh	Fd	165	593	2	25.9	Dystric and Eutric Brunisols	90	5	4	6	6
	2	IDFdm/xh	Fd/Pl	220	866	6	24.5		70	2	12	4	20
	3	IDFdm	Fd	122	1,223	14	22.5		102	23	21	8	7
Vaseux	1	IDFxh	Fd/Lw	312	1,123	10	23.3	Eutric Brunisols	95	3	15	4	10
	2	IDFxh	Pp	181	809	17	25.1		85	5	10	6	17
	3	PPxh	Pp	252	929	16	24.8		89	4	5	7	8

[1] From BC Ministry of Forests and Range Inventory Branch data

[2] Forest cover may have differed by transect. Codes E= Birch (*Betula paperyfera*), Ac=Black cottonwood (*Populus balsamifera*), Fd= Douglas-fir (*Pseudotsuga menziesii*), Lw= Larch (*Larix occidentalis*), Pl= Lodgepole pine (*Pinus contorta*), Pp= Ponderosa pine (*Pinus ponderosa*), Sx= Spruce (hybrid) (*Picea* cross), At = Trembling aspen (*Populus tremuloides*), B= True fir (*Abies lasiocarpa*)

[3] Categorical variable were assigned as follows: 316-45° = North,46-135° = East, 136-225° = South,226-315° = West

[4] http://genetics.forestry.ubc.ca/cfgc/ClimateBC/Help.htm

[5]From soil survey http://atlas.agr.gc.ca

The choices of locations for the study sites in this project were limited by the patchy nature of wildfire as well as road access. As it was impossible to tell the actual nature of the fire severity and real boundaries from existing fire maps, ground-truthing was required. Sites were chosen on the ground where burn severity could be confirmed and similar available unburned sites existed. For this reason, the forest cover mapping data may be diminished in accuracy, as the forest cover and vegetation at some sites was completely burned off.

2.2.2. Soil sampling and measurements

The sampling was done during July-August 2005 (i.e., one or two years following the fire). The sampling season had infrequent rain, which is typical for the region, and we made sure that sampling was conducted at least 24 hours following a rain event.

Within each of the eight fire sites, three areas were chosen at different elevations and/or aspects. In each area, a 50 m long transect was placed across the slope in a burned area and a ‘control’ transect was laid out in an adjacent unburned area. To aim for relative consistency in burn severity, burned areas had a crown burn resulting in loss of at least 90% of the foliage and a ground burn that removed the forest floor. It was impossible to choose these locations prior to visiting the field, due to fire boundary mapping inconsistencies and fire severity variability. Figure 2-2 outlines the relationship between fire sites, areas, transects, plots and water repellency tests.

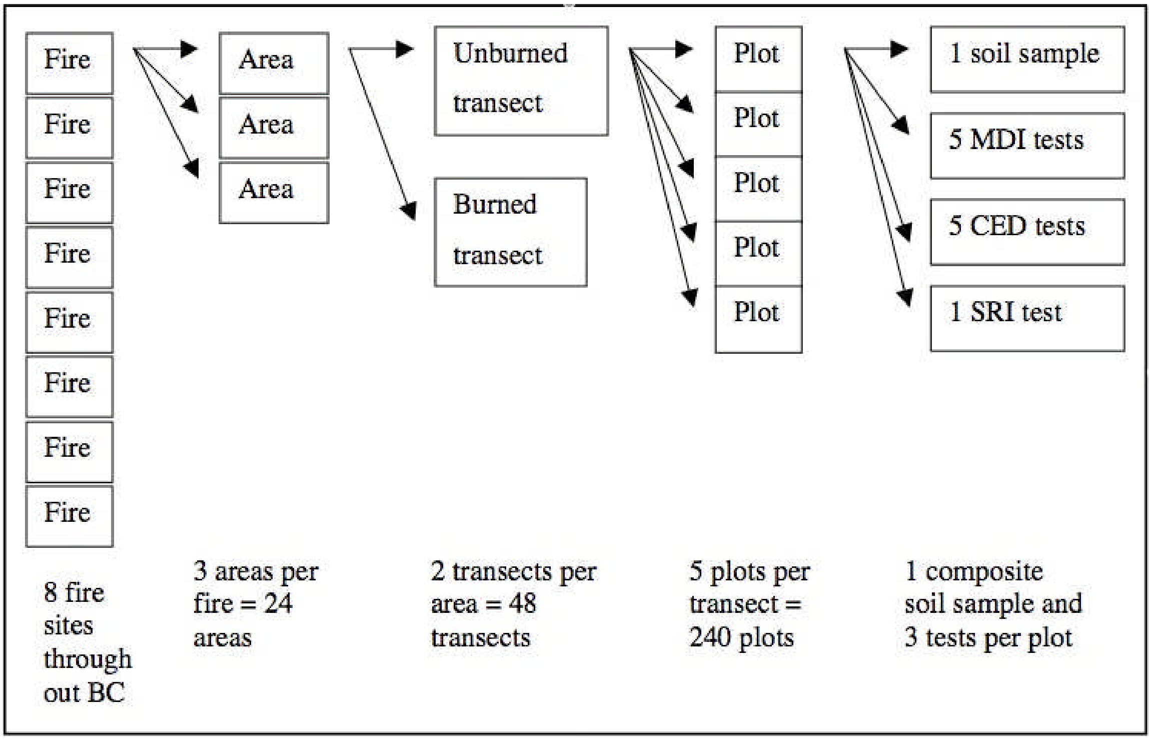


Figure 2-2: Sampling strategy and testing. Fire sites with area, transect and plot groupings

Five plots were sampled 10 m apart along each of the burned and unburned transects. Rocky areas were avoided because of lack of soil. At each plot, I gently scraped the organic material or charred/ash material back to expose the top layer of mineral soil in a 50 cm x 50 cm area.

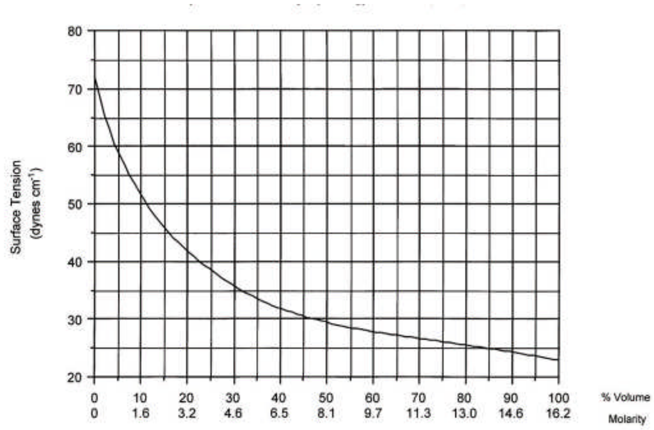
At each plot I took one SRI measurement and five each of the Mini-Disk Infiltrometer and Concentration of Ethanol Drop tests. Sampling points in the plots were chosen randomly but were far enough apart to not interfere with each other. Latitude and longitude were taken for the starting plot for each transect. Slope and aspect were recorded for each plot. At each plot, major vegetation was recorded, as well as canopy and understory tree species. After the SRI, MDI and CED tests were completed, I carefully collected one sample at the 0-10 mm depth at each of the five plots along the transects and mixed them to create one composite sample per transect for laboratory analyses.

The composite soil sample was taken to the MFR Kalamalka Research Station in Vernon, BC and air dried for 48 hours in a shed. Sub-samples were removed prior to air drying to determine the field soil moisture at each plot. Once the samples had air dried, they were sieved to 2 mm and put into a large oven at 60º C for 48 hours. Then they were cooled and bagged for transport to the lab. Between repetitions of tests, they were re-dried at 60º C for 48 hours. I chose 60° C because it is similar to field temperatures for burned soils in hot, dry southern BC for low-clay content soils (Stathers et al., 1985).

2.2.2 Field water repellency tests

2.2.2.1 Concentration of Ethanol Drop test

A proxy test for contact angles is a simple test called the Concentration of Ethanol Drop (CED), which determines the surface tension required for a liquid to pass over the surface of the soil particles (Roy & McGill, 2002). This is also called the Molarity of Ethanol Drop test (MED) (Roy & McGill, 2002), or Critical Surface Tension test (CST) (Letey et al., 1962). The CED test uses a range of concentrations of ethanol to measure the lowest concentration that does not bead on the soil surface. Drops of the ethanol of increasing concentration are placed on the soil surface. Droplet absorption is timed from when the drop touches the soil, and stops as soon as the drop starts to enter the soil. If the drop did not absorb within a set time of five seconds, the next higher percent of ethanol is dropped onto the soil surface. Figure 2-3 shows that the surface tension decreases as ethanol concentration increases, but not at a linear rate. The rate of decrease in surface tension with respect to ethanol concentration decreases at ethanol concentrations greater than 40%.



(Letey et al.,2000)

Figure 2-3: The surface tension of ethanol is not linearly related to its concentration/molarity

In these tests, ethanol was dropped in increasing concentrations onto the surface of the mineral soil immediately next to where the other tests were done (Figure 2-4). When two or three drops took longer than five seconds to absorb into the soil, two or three drops of the next highest concentration were dropped. The concentrations used were: 0, 1, 2, 3, 4, 5, 10, 15, 20, 30, and 40% by volume.

Figure 2-4: The Concentration of Ethanol Drop test showing a drop of ethanol solution beading on the soil surface

2.2.2.2 Water Drop Penetration Time

The Water Drop Penetration Time test (Bachmann et al., 2003) involves recording the time taken for drops of water to infiltrate. This study attempts to try two modified versions of this test to determine a simple, practical method of water repellency intensity testing - the Mini-Disk Infiltrometer (MDI), which was tested in the field and the lab, and the Spatial Repellency Index (SRI), which was only tested in the field.

2.2.2.3 Mini-Disk Infiltrometer

Mini-Disk Infiltrometers are compact infiltrometers with a porous steel disk at the base, and an adjustable suction tube in a separate chamber at the top (Figure 2-5). The cylinders are marked like graduated cylinders so that the volume of water sucked out the bottom of the tube can be viewed. It is intended to measure the hydraulic conductivity of the soil (Decagon Devices, 2011).

In this case, one measurement was made at each of five random spots within the plot. The bottom chamber was filled with water, and then the upper suction was set at a low 5 mm tension for all measurements. Then the MDI was placed on the soil for one minute, and the total volume of water drawn out of the infiltrometer was recorded. The five measurements per plot were averaged for statistical analyses. This tension is considered a small negative head, where soil draws water into itself, as opposed to conventional, positive head infiltrometers that push water into the soil.

Figure 2-5: A Mini-Disk Infiltrometer in the field. The top chamber is adjustable for different tensions

2.2.2.4 Spatial Repellency Index

This simple field test is intended to give an estimate of the spatial extent of the water repellent soils (Bachmann et al., 2003; Dekker et al., 1999; Doerr et al., 2006). A small amount of water was drizzled from a squirt bottle along a very shallow (5 mm deep) trench within the plot (Figure 2-6). The purpose of the trench was to stop the water droplets at the surface from rolling down the slope. The percentage of the length of trench that was totally wettable, partly wettable or totally water repellent was estimated. The definition of "partly wettable" was that the water drop would not be immediately adsorbed onto the soil. "Totally water repellent" meant that the water drop remained intact on the surface for more than 60 seconds

To analyze these measurements, the three classes were given a weight of 1 for totally wettable, 5 for partly wettable and 10 for totally water repellent. Then the percentage of each class was multiplied by the weight and summed for a unitless, numerical value for repellency.

Figure 2-6: Water being dribbled from a squeeze bottle along a shallow 'trench' across the slope to determine the Spatial Repellency Index

2.2.3 Laboratory water repellency tests

2.2.3.1 Mini-Disk Infiltrometer

The sieved, air dried and oven dried (at 60 ºC for 48 h) soil was placed carefully in a 25 cm round aluminum pan. The layer of soil was >35 mm deep, so that the bottom and sides of the pan would not interfere with the measurement.

The tests were repeated five times on the dried samples, and the average measurement used for analysis. The samples had to be re-dried twice because there was only enough soil to take two measurements at the same time. After re-drying, the samples were crushed to break up any aggregates that had formed from the previous wetting.

2.2.3.2 Concentration of Ethanol Drop

The laboratory ethanol measurement was determined just once on the composite soil samples, using the same technique with increasing concentrations as was done in the field.

2.2.3.3 Spatial Repellency Index

The Spatial Repellency Index was not used in the laboratory as it is inappropriate for small and disturbed samples.

2.2.4 Statistical analysis

Simple Pearson’s correlations, unpaired, dependent t-tests and one and two way ANOVAs were performed to analyze the data in this chapter. Note for the ANOVAs that in some cases the assumptions for normality were not met regardless of various different transformations of the data. ANOVA tables can be found in Appendix B.

2.3 Results

2.3.1 Comparisons within tests

2.3.1.1 Mini Disk Infiltrometer

MDI measurements on soil from the same plot in the field and after drying and sieving in the laboratory (Figure 2-7) showed a positive relationship. MDI readings in the laboratory were higher than field measurements for the same soil, meaning that soils in the laboratory were not as repellent. The results of the MDI tests showed significant differences in the field and the laboratory (Figure 2-8).The overall average field measurement was 7.8 mL/min and the average laboratory measurement was 19.6 mL/min.

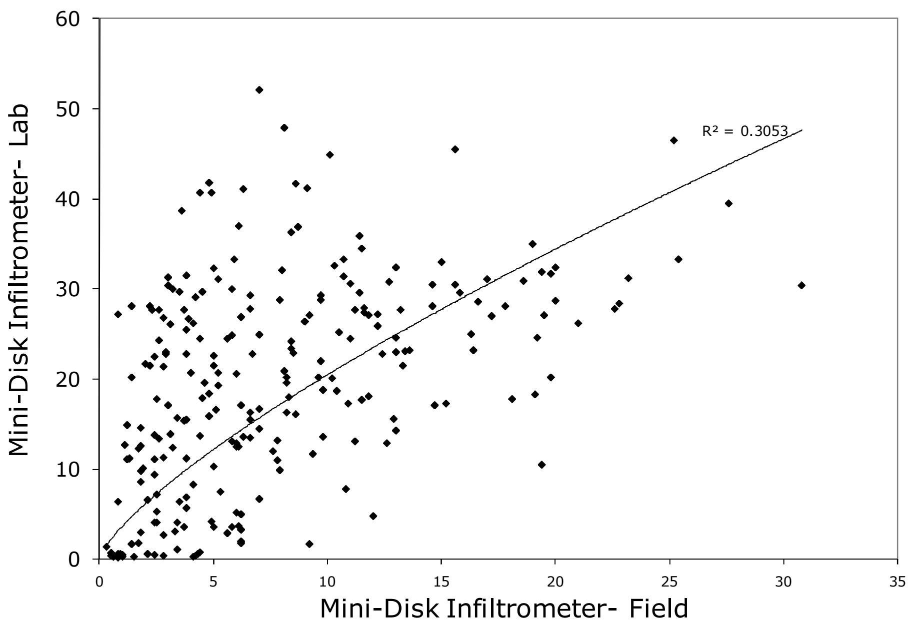


Figure 2-7: Mini-Disk Infiltrometer measurements on soil in the field and after drying and sieving in the lab

Figure 2-8 shows the average MDI readings at each fire, as determined in the field and in the lab. For field measurements, the most repellent soils were on the Kuskonook and McLure fires, and the least repellent results were found at the Okanagan Mountain Park and Vaseux Lake fires. Once the soils were dried and sieved, the most repellent soils were from the Kuskonook and Lamb Creek fires, and the least repellent from the Town Creek, Okanagan Mountain Park and Vaseux Lake fires. The lab measurements were significantly higher than the field measurements for the McLure, Town Creek, Okanagan Mountain Park and Vaseux Lake fire sites (see ANOVA tables in Appendix B). The laboratory MDI for Town Creek, Okanagan Mountain Park and Vaseux Lake indicated significantly higher measurements than the other fire sites. Kuskonook had significantly lower measurements than the other sites. Note that lower measurements indicated higher water repellency.

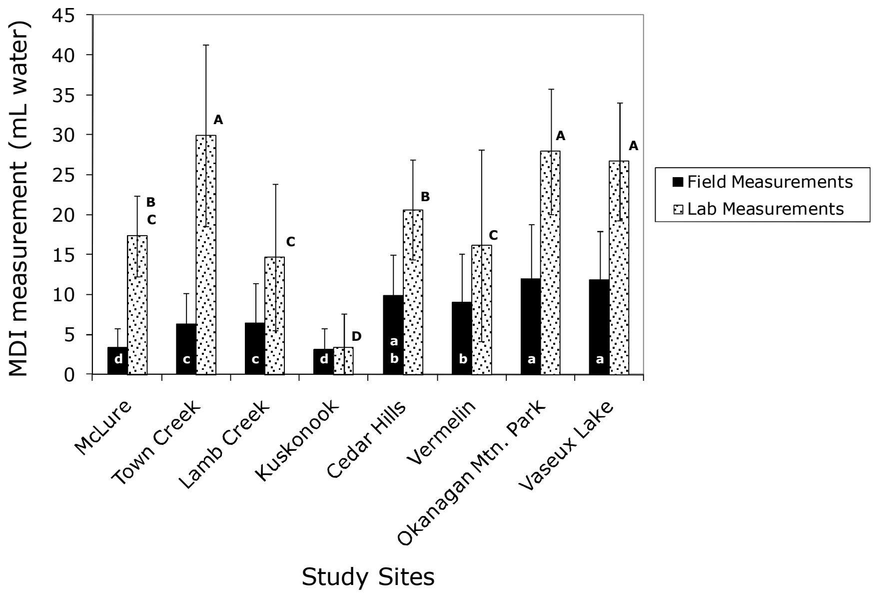


Figure 2-8: Mini-Disk Infiltrometer measurements from the field and the laboratory for each of the eight fire sites included in this study. Error bars show one standard deviation (n= 15). For each of field or laboratory measurements, columns not labeled by the same letter are significantly different using ANOVA.

2.3.1.2 Concentration of Ethanol Drop

The CED tests on soils in the field and the laboratory also showed that the soils were more repellent in the field than in the laboratory (with means of 8.1 in the field and 6.0 in the lab; t-test of all measurements resulted in p= 0.0002). There is a significant positive relationship between field and laboratory assessments of wettability by CED (Figure 2-9), but the soils in the field were not significantly more or less repellent than in the laboratory (Figure 2-10) (note that higher readings indicate more repellent soils).

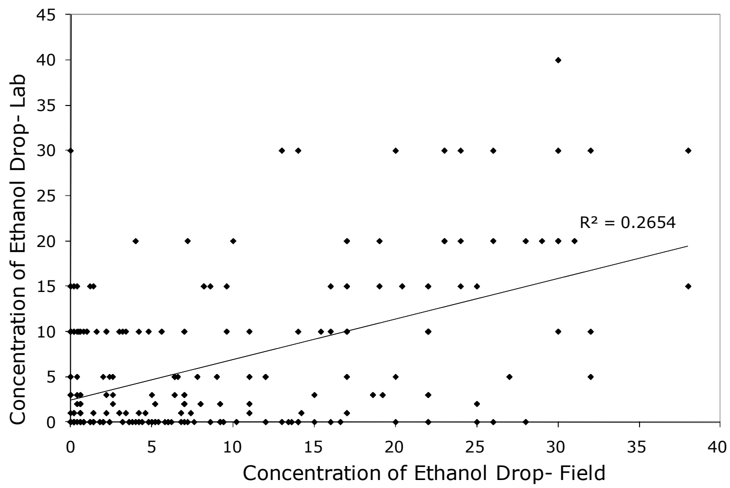


Figure 2-9: Concentration of Ethanol Drop measurements on soil from the same plot in the field and after drying and sieving in the lab.

Soils from Kuskonook showed the highest repellency in the field and the laboratory (Figure 2-10). Vaseux Lake and Cedar Hills showed the lowest repellency in the field, and Town Creek and Vaseux Lake showed the lowest repellency in the laboratory with this method. Field and laboratory measurements were not significantly different at any of the fire sites according to the results of the CED method.

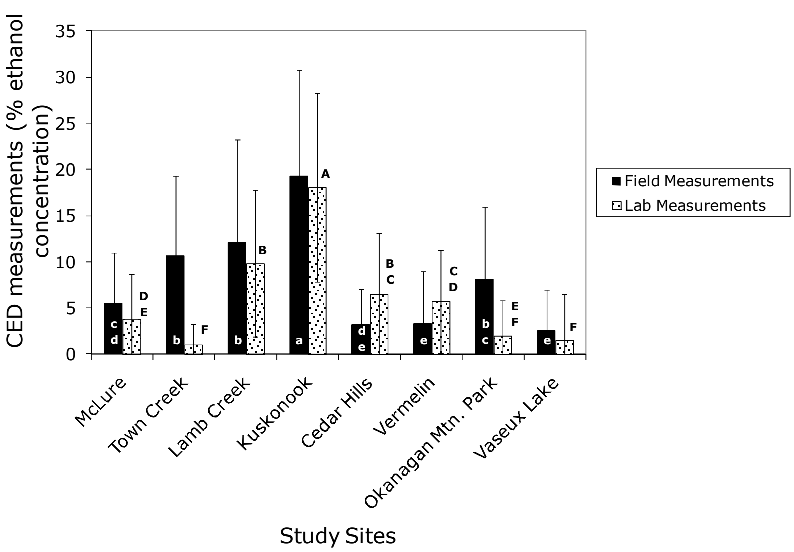


Figure 2-10: Concentration of Ethanol Drop test values for all soils at each fire, showing the mean of measurements taken in the field and in the lab. Error bars show one standard deviation (n=15). For each of field and laboratory measurements, columns not labeled by the same letter are significantly different using ANOVA.

2.3.1.3 Spatial Repellency Index

The Kuskonook fire site showed the highest average repellency with the SRI method, and Vaseux Lake showed the lowest (Figure 2-11). The SRI test was performed on 7 of the 8 forest fires sites - it was not performed on the McLure fire. The highest values indicate the highest repellency. One-way ANOVA on untransformed data showed significant differences between the fire sites, with Kuskonook having the highest repellency and Vaseux Lake the lowest.

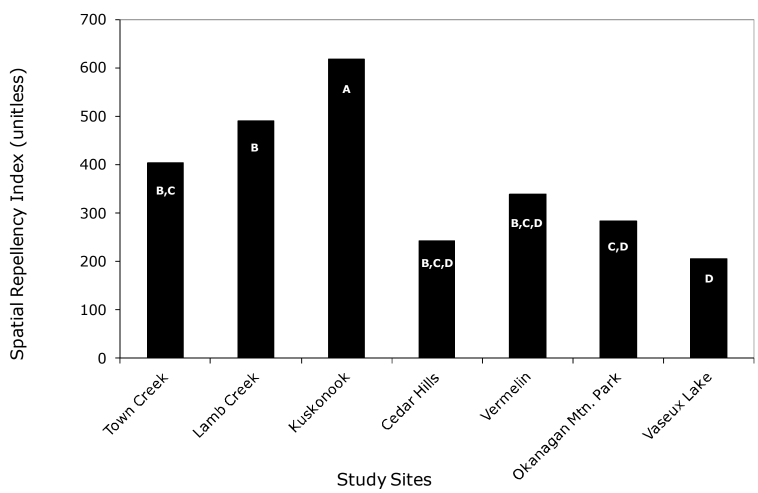


Figure 2-11: Mean result for Spatial Repellency Index at seven of the fire sites. Columns not labeled by the same letter are significantly different using ANOVA.

2.3.2 Comparisons between tests

There were significant negative correlations between measurements of water repellency tested by the MDI and the CED in the laboratory (Figure 2-12). Note that higher MDI values and lower CED values indicate higher water repellency.

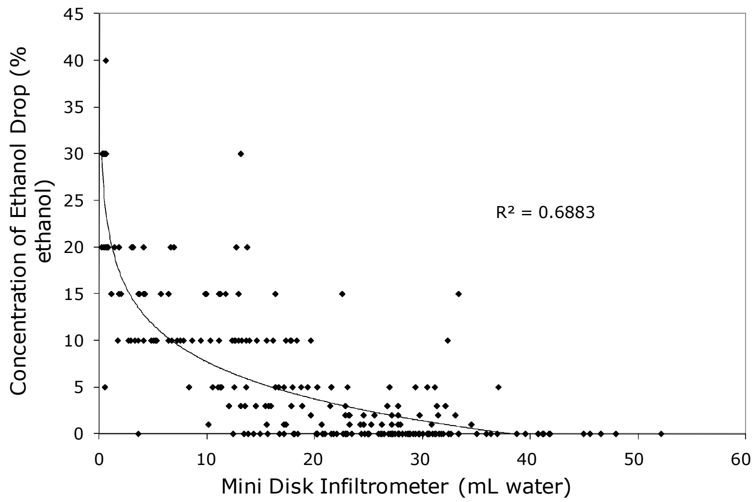


Figure 2-12: Mini-Disk Infiltrometer and Concentration of Ethanol Drop results for the same soil samples when measured in the lab

As in the lab measurements (Figure 2-12), there is agreement between the two tests of repellency, MDI & CED, but the relationship is weaker than in the lab data because of a greater scatter (Figure 2-13).

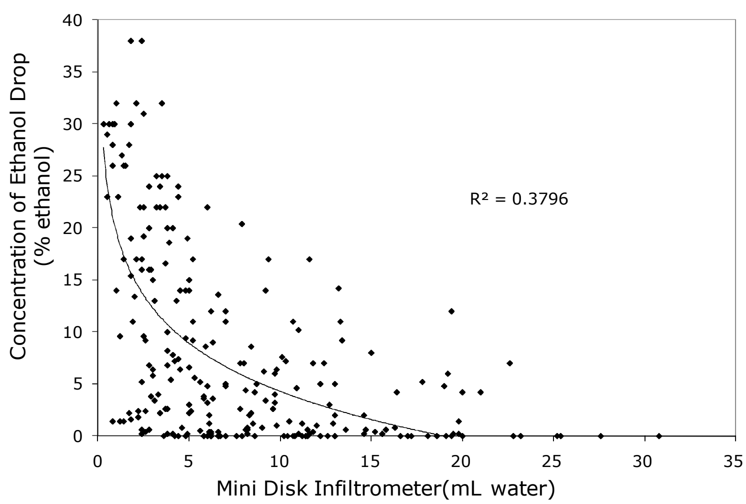


Figure 2-13: Mini-Disk Infiltrometer and Concentration of Ethanol Drop tests for the same soil samples in the field

When I compared SRI to MDI measurements, there was no significant relationship. Figure 2-14 shows the average results for all of the plots. This was unexpected since both tests used water, however the MDI may be more sensitive to other soil characteristics.

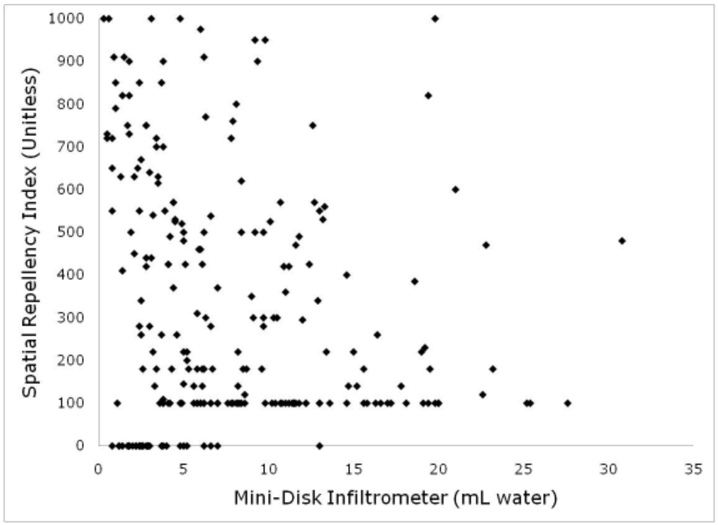


Figure 2-14: Spatial Repellency Index compared to Mini-Disk Infiltrometer for all plots.

Unlike MDI, CED was significantly correlated to the SRI measurements (Figure 2-15).

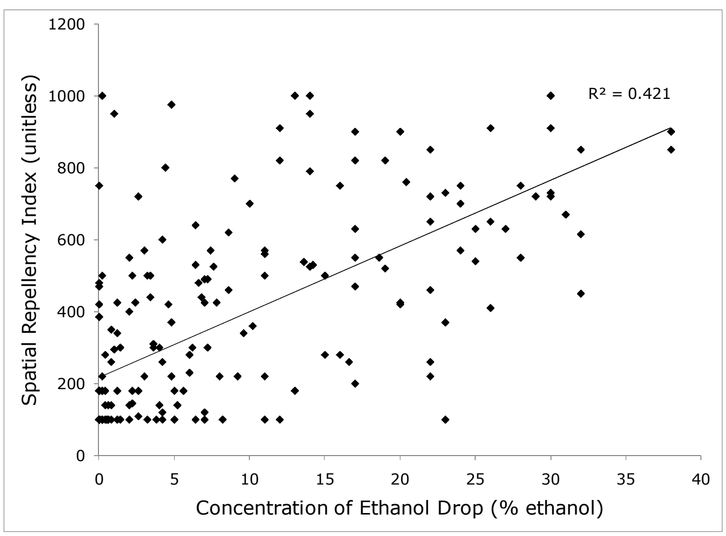


Figure 2-15: Repellency Index compared to Concentration of Ethanol Drop for all plots.

Figure 2-16 shows the differences between the MDI, SRI and CED tests in the field. Kuskonook showed the greatest repellency with all three of the tests, and Vaseux Lake tied with Okanagan Mountain Park for the lowest repellency with the MDI. Vaseux Lake had the lowest repellency with the CED and the SRI. Lower MDI values indicate greater repellency while lower CED and SRI scores indicate lower repellency. SRI (and the standard deviation) has been divided by a factor of 30 for graphing purposes for Figure 2-17 only.

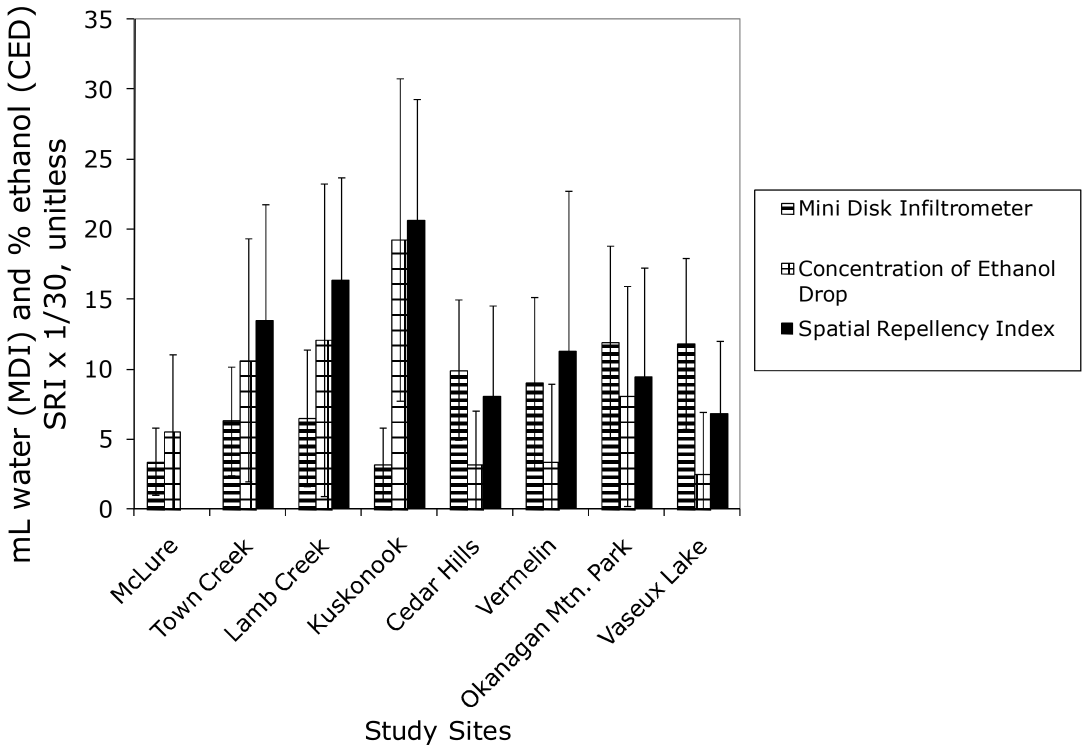


Figure 2-16: Mean Mini-Disk Infiltrometer, Concentration of Ethanol Drop and Spatial Repellency Index for soils from each fire, tested in the field. Error bars represent one standard deviation (n=30).

The various site characteristics shown in Table 2-1 may help to explain why Kuskonook soils are more repellent and why Vaseux and Okanagan Mountain Park are less repellent. Kuskonook sampling areas were in the ESSF BEC zone at a higher elevation, and have maximum mean temperatures for the summer months that are about 6°C cooler than Okanagan Mountain Park and Vaseux Lake. The latter two fire sites are at lower elevation and are mostly located in the IDF and PP BEC zones. Soil texture was coarser at Kuskonook (average SSA was 68.8) than Okanagan Mountain Park (87.3) and Vaseux Lake (89.6). Kuskonook did have the coarsest texture, but Okanagan Mountain Park and Vermelin had the third and second coarsest texture, respectively. Although Kuskonook, Okanagan Mountain Park and Vaseux Lake sit at opposite ends of the repellency measurements, they do not sit at opposite ends of the measurements for other site characteristics. Texture and other site characteristics will be analyzed further in Chapter 3.

For all of the tests, the soils from the Kuskonook site showed the highest repellency in both the laboratory and the field of all of the fires sampled in this study. Soils from the Vaseux Lake fire had the lowest repellency results in the field for the three tests, but the Town Creek fire had the lowest results in the lab. Table 2-2 outlines these results.

Table 2-2: Sites with the highest and lowest soil repellency obtained by all tests measured in field and laboratory

Test	**Most repellent sites**	**Least repellent sites**
MDI in the field	Kuskonook	Okanagan Mtn Park/Vaseux Lake
MDI in the lab	Kuskonook	Town Creek
CED in the field	Kuskonook	Vaseux Lake
CED in the lab	Kuskonook	Town Creek
SRI (field only)	Kuskonook	Vaseux Lake

2.4 Discussion

While the results of this study showed a significant relationship between water repellency measurements in the field and in the laboratory using either the MDI or CED test, the relationships were not well defined. This is similar to a study by Dekker et al., (2001), who used the WDPT test in the field and laboratory, and also found high spatial and temporal variability in water repellency. They found that water repellency was sometimes higher when measured in the field than on heated, dried samples in the laboratory, and sometimes the opposite was true. Douglas et al. (2007) also compared CED against WDPT after drying soils at different temperatures (between 20° and 105°C), and in their study samples were also sieved through a 2 mm sieve. They found a range of repellencies for soils with hydrophobic organic coatings, and attributed the water repellency at a given time to be related to the “state into which the organic materials adsorbed on its particle surfaces have been locked by the environmental history of the soil”. Doerr et al. (2009) compared WDPT measurements *in situ* and in the laboratory for soils from coniferous forests in the northwestern United States. In both field and laboratory conditions, 75% of their soil samples were water repellent. However, extreme repellency was exhibited by 60% of the samples in the field but only 49% in the laboratory. This is in line with the trends seen in my study.

Tillman et al. (1989) also compared *in situ* and laboratory water repellency tests using intrinsic sorptivity measurements, and found that sieving the soil made it less repellent, but that incubation for 3h (temperature not provided) restored at least some of the repellency. Their methods were quite different than those used in this study.

In the field and in the laboratory, MDI and CED were significantly correlated. In the field, SRI and CED were correlated, but SRI and MDI were not. The MDI and CED comparison results are similar to the literature reviewed. Douglas et al., (2007) also found significant similarities when testing CED against WDPT, and used the CED to test for initial severity of water repellency and WDPT to assess its persistence. Roy & McGill (2002) used the CED test and caution against direct comparisons with WDPT because the WDPT test has unlimited duration of solid-liquid contact time.

Buczko and Bens (2006) compared the WDPT test against the sessile drop method for precise contact angle measurement on oven dried (at 60°C for 3 days) soils from northeastern Germany. They found a cluster of WDPT results obtained at >5 s around a 90° contact angle, which confirmed that 5 s is a good time threshold for assessing water repellency. I also used 5s as the criteria for determining repellency with both of the WDPT methods.

2.5 Conclusion

Any of the three tests evaluated in this study could be used to test for repellency, however data can only be compared across the same method of determination (e.g., all field measurements, all laboratory measurements, all CED, all MDI or all SRI) In other words, it would be inappropriate to compare measurements in the field with measurements in the laboratory, or results from CED directly with results from MDI.

Differences between the field and laboratory results vary due to the drying, heating and physical abrasion of soils when preparing samples for laboratory tests. Generally, the field measurements showed higher repellency than the laboratory measurements. The field testing was done *in situ*, with just the organic layers gently removed and the rest of the soil undisturbed. The laboratory measurements for the MDI and CED tests may have shown a stronger correlation because of the homogenization of the soils during the sampling and preparation processes, and destruction of the water repellent compounds as the aggregates were broken down due to drying, sieving and smoothing of the tested surface.

All three water repellency tests (CED, MDI and SRI) indicated that soils from the Kuskonook area had the highest water repellency. However, results for the lowest water repellency were more variable with both MDI and CED field tests giving different results than their respective laboratory tests. This suggests that field measurements should not necessarily be compared directly with laboratory measurements.

The MDI or CED tests can both be used in the field or laboratory to determine the presence and degree of water repellency. When I compared field results to laboratory results within tests, the CED test had a slightly stronger relationship than the MDI. Both the MDI and CED tests are quick and relatively simple, requiring basic equipment & materials to execute.

The SRI test is useful in determining presence/absence of repellency, but not for the degree of repellency. By comparing the SRI results to those of the CED tests, we see that it is a reliable method to detect the presence or absence of water repellency and conduct a rapid spatial repellency assessment in the field. An implication of this is that the SRI may be useful for land managers interested in whether their soils are repellent, but it is not useful for anyone needing specific information on the degree of repellency.

Chapter 3: Factors affecting soil water repellency after wildfire in southern British Columbia

3.1 Introduction

While the literature on the development and persistence of repellency of forest soils has included results from numerous regions around the world, there are still some regions (such as British Columbia) whose soil water repellencies have not been examined extensively. While some other geographical areas have been studied as far back as the 1960s, there has been very little research on water repellency of forest soils in British Columbia (BC). At the time of this field research, two studies were published: Henderson & Golding (1983) studied water repellency persistence after prescribed burning in two Greater Vancouver (coastal) municipal watersheds. They found that slash burning increased the presence of water repellency for two years after the fires. Repellency was found at 0-4cm depth but not at 8-10 or >15cm below the humus. Barrett & Slaymaker (1989) tested soils at unburned subalpine sites throughout southern BC, and found that water repellency in soils increased with total organic matter.

Generally, it is assumed that wildfire increases the occurrence of soil water repellency. During the fire, heat can volatilize organic compounds, forcing them deeper into the soil according to temperature or concentration gradients (DeBano, 2000b). This creates a layer of coated soil particles under the soil surface (DeBano & Conrad, 1978). Coarser soils have been found to generally be more water repellent than finer textured soils. Sand particles have fewer bonding sites for hydrophobic substances than clay particles characterized by a large specific surface area (DeBano, 1981; Harper & Gilkes, 1994; Scott, 2000, Regalado et al., 2008). The relationship between the water repellency and particle size (texture) is not always straightforward. For example, Scott (2000) found that the specific surface area of the soil was not a significant predictor of water repellency on several soils in South Africa. He found that the organic carbon content did play a significant role in predicting water repellency. de Jonge et al. (1999) also found that particle size alone did not explain the occurrence of water repellency in soils from Denmark and that properties such as water content and drying temperature had a greater impact.

Water repellency has also been associated with certain types of plant species. Plants with waxy coatings on their leaves, such as heath scrub, *Pinus radiata*, citrus trees, chaparral vegetation and eucalyptus trees are the most common type of vegetation found on sites with water repellent soils (Bond, 1969; Scott, 2000; Leighton-Boyce et al., 2005). As the fallen leaves break down, the organic matter is less likely to be polar and therefore less wettable than organic matter from other types of plants without the wax-like coatings.
The amount and type of organic matter may play critical roles in water repellency, according to Dekker & Ritsema (1994a), Ellerbrock et al. (2005) and Jaramillo et al. (2000). Water repellency is thought to depend on the orientation of hydrophobic and hydrophilic groups on the organic molecules. At certain temperatures, these organic molecules can change orientation so that hydrophobic or hydrophilic groups are exposed to the soil solution. Drier soils tend to be more repellent (Jaramillo et al., 2000; King, 1981; Dekker et al., 2001), although moisture conditions are not necessarily a good indicator of soil water repellency. Dekker et al. (2001) found water repellency below a critical zone, with upper and lower threshold levels of soil water content. Bayer and Shaumann (2007) showed that soils were severely repellent if their pH was 3.0 or less, which is unnaturally low, therefore pH was not one of the soil characteristics tested in this study.

The objective of this study was to evaluate indicators (texture, soil organic matter, soil water content, elevation, aspect, slope, and forest type) as potential predictors of water repellency in southern BC. Factors such as elevation, aspect, slope, forest cover type and biogeoclimatic (BEC) zone affect the soil organic matter through productivity, effects on temperature and the type of organic matter on the site. These ‘other’ factors were included in the models as categorical variables to determine their contribution to water repellency in these soils.

Hypotheses associated with this study objective were that environmental factors and conditions that have been found to affect water repellency in similar studies in other regions could be used to predict the presence of post-fire water repellency in BC:

1. Wildfire that burns the litter layer and fine tree branches will increase the existence of water repellency in soils.
2. Greater organic matter content in the soil will increase the degree of water repellency in all tests used.
3. Drier soils will have higher instances of water repellency.
4. Soils with greater specific surface area measurements will have lower incidence of water repellency in all tests.

3.2 Materials and methods

3.2.1 Study sites

Soil samples were taken from eight areas in southern BC that had been burned by wildfires. The areas were selected between the Coastal Mountains to the west and the Rocky Mountains to the east, and the US border to the south and to the town of Barriere to the North. These fire sites were chosen for this study based on the following criteria: (1) relatively large size, (2) a wildfire in 2003 or 2004, (3) a broad network of roads throughout for good access, and (4) observation of soils exhibiting hydrophobicity (a Forest Practices Board report from February 2005 identified Cedar Hills, Kuskonook and Lamb Creek as having hydrophobic soils that caused debris flows after the wildfire).

The study locations (Figure 3-1) were:

1. Okanagan Mountain Park (southeast of Kelowna),
2. Vaseux Lake (near Okanagan Falls),
3. Town Creek (just north of Lillooet),
4. Lamb Creek (south of Cranbrook),
5. Kuskonook (north of Creston),
6. Cedar Hills (outside of Falkland),
7. Barriere/McLure (around Barriere), and
8. Vermelin (north of North Barriere Lake).

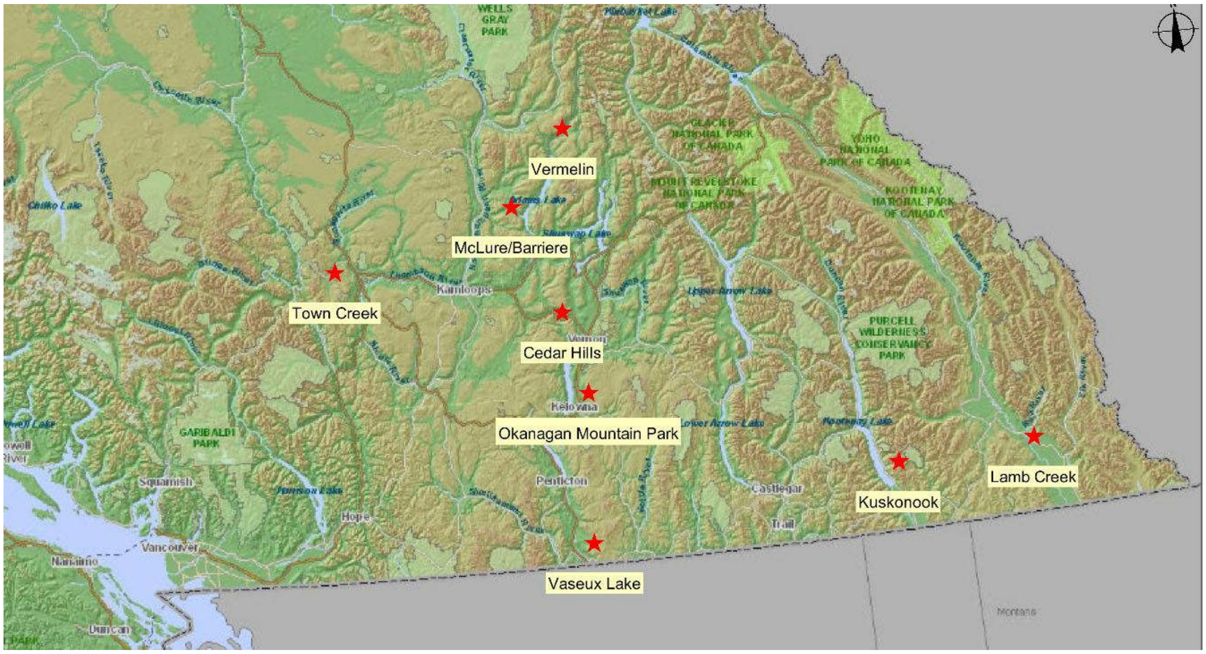


Figure 3-1: Study areas in southern British Columbia

Specific BEC zone, subzone, elevation range, soil type, soil texture and maximum July temperature are outlined for each study area in table 3.1. Note that these were not used to stratify the plots during the design of these studies; rather, the data is presented for descriptive purposes. **Appendix A** describes more information on each fire.

Table 3-1: Site and soil characteristics of the fire areas included in this study

Fire site	Area #	BEC Zone	1° Forest cover	Aspect (degrees)	Average elevation (masl)	Slope	Max. mean July Temp. (1971-2000)[4]	Soil type[5]	Average Soil Specific Surface Area (m^2/g)	Average soil moisture content (%)		Average soil total organic matter (%)	
										Burned	unburned	Burned	unburned
McLure/ Barriere	1	MSdm	Pl/S	88	1,241	17	21.7	Humo-Ferric Podzols/ Gray Luvisols	165	15	26	5	8
	2	IDFmw/xh	Fd	251	954	19	23.8		118	28	27	12	6
	3	ICHmk/ IDFmw	E	122	985	17	22.9		124	24	26	10	6
Town Creek	1	MSxk	Pl	218	1,417	15	21.8	Dystric and Eutric Brunisols	150	15	36	10	11
	2	IDFdc	Fd/Pl	167	1,389	35	22		137	7	14	10	11
	3	IDFdc	Fd/Fd	133	1,179	23.5	22.8		108	20	31	11	11
Lamb Creek	1	ESSFdm	Pl	182	1,642	15	18.8	Orthic Humo-Ferric Podzols	76	13	25	11	10
	2	ESSFdk	Pl	100	1,948	13	19.4		142	24	33	8	14
	3	ESSFdk	Pl	45	1,652	15	20.2		135	31	30	9	10
Kuskonook	1	ESSFdmw	Pl	228	2,014	17	18.7	Humo-Ferric Podzols & Orthic Dystric Brunisols	80	4	15	9	16
	2	ESSFdmw	B	185	2,020	15	19.1		71	7	10	9	9
	3	ESSFdm	Pl	240	1,807	28	19.2		55	7	17	6	9
Cedar Hills	1	IDFmw	Fd	226	1,183	17	22	Humo-Ferric Podzols	83	11	16	6	11
	2	IDFmw	At/C	169	878	17	23.7		123	9	8	4	10
	3	IDFmw	At	155	922	4	23.3		104	18	6	5	8
Vermelin	1	ESSFwc	Sx	188	1,603	20	19	Humo-Ferric Podzols	81	8	22	5	6
	2	ESSFwc	Ac/Sx	249	1,541	14	19.3		90	18	23	4	5
	3	ICHdw	Fd/Pl	146	659	25	23.5		55	5	18	5	7

Fire site	Area #	BEC Zone	1° Forest cover	Aspect (degrees)	Average elevation (masl)	Slope	Max. mean July Temp. (1971-2000)[4]	Soil type[5]	Average Soil Specific Surface Area (m^2/g)	Average soil moisture content (%)		Average soil total organic matter (%)	
										Burned	unburned	Burned	unburned
Okanagan Mountain Park	1	IDFxh	Fd	165	593	2	25.9	Dystric and Eutric Brunisols	90	5	4	6	6
	2	IDFdm/xh	Fd/Pl	220	866	6	24.5		70	2	12	4	20
	3	IDFdm	Fd	122	1,223	14	22.5		102	23	21	8	7
Vaseux	1	IDFxh	Fd/Lw	312	1,123	10	23.3	Eutric Brunisols	95	3	15	4	10
	2	IDFxh	Pp	181	809	17	25.1		85	5	10	6	17
	3	PPxh	Pp	252	929	16	24.8		89	4	5	7	8

[1] From BC Ministry of Forests and Range Inventory Branch data

[2] Forest cover may have differed by transect. Codes E= Birch (*Betula paperyfera*), Ac=Black cottonwood (*Populus balsamifera*), Fd= Douglas-fir (*Pseudotsuga menziesii*), Lw= Larch (*Larix occidentalis*), Pl= Lodgepole pine (*Pinus contorta*), Pp= Ponderosa pine (*Pinus ponderosa*), Sx= Spruce (hybrid) (*Picea* cross), At = Trembling aspen (*Populus tremuloides*), B= True fir (*Abies lasiocarpa*)

[3] Categorical variable were assigned as follows: 316-45° = North,46-135° = East, 136-225° = South,226-315° = West

[4] http://genetics.forestry.ubc.ca/cfgc/ClimateBC/Help.htm

[5] From soil survey http://atlas.agr.gc.ca

The choices of locations for the study sites in this project were limited by the patchy nature of wildfire as well as road access. As it was impossible to tell the actual nature of the fire severity and real boundaries from existing fire maps, ground-truthing was required. Sites were chosen on the ground where burn severity could be confirmed and similar available unburned sites existed. For this reason, the forest cover mapping data may be diminished in accuracy, as the forest cover and vegetation at some sites was completely burned off.

3.2.2 Soil sampling and measurements

The sampling was done during July-August 2005 (i.e., one or two years following the fire). The sampling season had infrequent rain, which is typical for the region, and we made sure that sampling was conducted at least 24 hours following a rain event.

Within each of the eight fire sites, three areas were chosen at different elevations and/or aspects. In each area, a 50 m long transect was placed across the slope in a burned area and a ‘control’ transect was laid out in an adjacent unburned area. To aim for relative consistency in burn severity, burned areas had a crown burn resulting in loss of at least 90% of the foliage and a ground burn that removed the forest floor. It was impossible to choose these locations prior to visiting the field, due to fire boundary mapping inconsistencies and fire severity variability. Figure 3-2 outlines the relationship between fire sites, areas, transects, plots and water repellency tests.

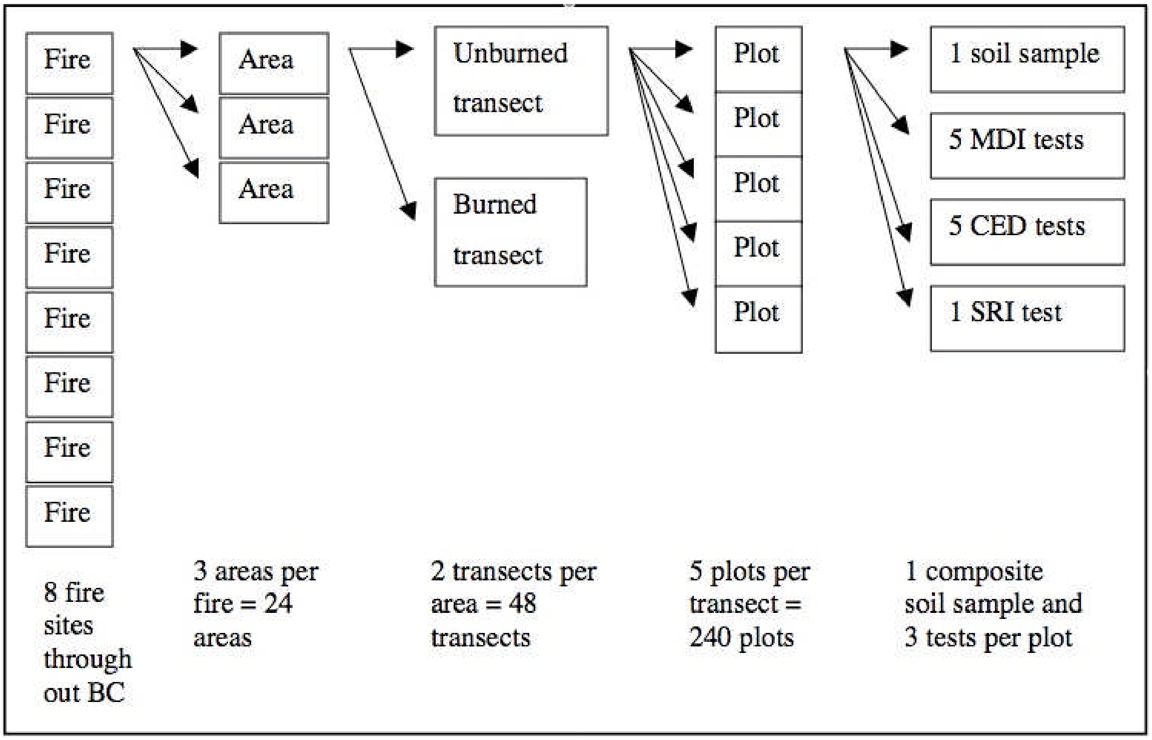


Figure 3-2: Sampling strategy and testing. Fire sites with area, transect and plot groupings

Five plots were sampled 10 m apart along each of the burned and unburned transects. Rocky areas were avoided because of lack of soil. At each plot, I gently scraped the organic material or charred/ash material back to expose the top layer of mineral soil in a 50 cm x 50 cm area.

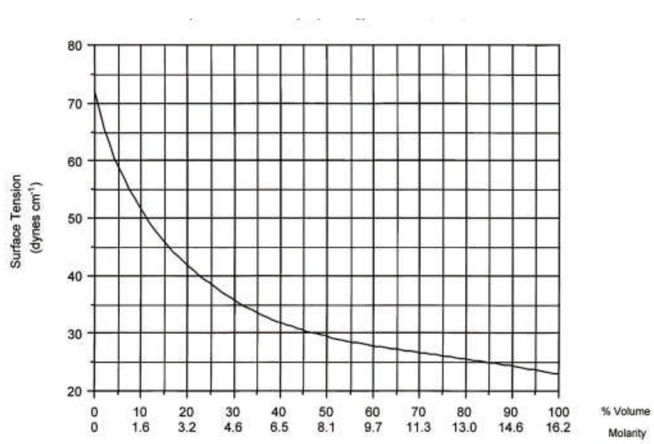
At each plot I took one SRI measurement and five each of the Mini-Disk Infiltrometer and Concentration of Ethanol Drop tests. Sampling points in the plots were chosen randomly but were far enough apart to not interfere with each other. Latitude and longitude were taken for the starting plot for each transect. Slope and aspect were recorded for each plot. At each plot, major vegetation was recorded, as well as canopy and understory tree species. After the SRI, MDI and CED tests were completed, I carefully collected one sample at the 0-10 mm depth at each of the five plots in each transect and mixed them to create one composite sample per transect for laboratory analyses.

The composite soil sample was taken to the MFR Kalamalka Research Station in Vernon, BC and air dried for 48 hours in a shed. Sub-samples were removed prior to air drying to determine the field soil moisture at each plot. Once the samples had air dried, they were sieved to 2 mm and put into a large oven at 60º C for 48 hours. Then they were cooled and bagged for transport to the lab. Between repetitions of tests, they were re-dried at 60º C for 48 hours. I chose 60° C because it is similar to field temperatures for burned soils in hot, dry southern BC for low-clay content soils (Stathers et al., 1985).

3.2.3 Field water repellency tests

3.2.3.1 Concentration of Ethanol Drop test

A proxy test for contact angles is a simple test called the Concentration of Ethanol Drop (CED), which determines the surface tension required for a liquid to pass over the surface of the soil particles (Roy & McGill, 2002). This is also called the Molarity of Ethanol Drop test (MED) (Roy & McGill, 2002), or Critical Surface Tension test (CST) (Letey et al., 1962). The CED test uses a range of concentrations of ethanol to measure the lowest concentration that does not bead on the soil surface. Drops of the ethanol of increasing concentration are placed on the soil surface. Droplet absorption is timed from when the drop touches the soil, and stops as soon as the drop starts to enter the soil. If the drop did not absorb within a set time of five seconds, the next higher percent of ethanol is dropped onto the soil surface. Figure 3-3 shows that the surface tension decreases as ethanol concentration increases, but not at a linear rate. The rate of decrease in surface tension with respect to ethanol concentration decreases at ethanol concentrations greater than 40%.



(Letey et al.,2000)

Figure 3-3: The surface tension of ethanol is not linearly related to its concentration/molarity

In these tests, ethanol was dropped in increasing concentrations onto the surface of the mineral soil immediately next to where the other tests were done (Figure 3-4). When two or three drops took longer than five seconds to absorb into the soil, two or three drops of the next highest concentration were dropped. The concentrations used were: 0, 1, 2, 3, 4, 5, 10, 15, 20, 30 and 40% by volume.

Figure 3-4: The Concentration of Ethanol Drop Test showing a dropof ethanol solution beading on the soil surface

3.2.3.2 Water Drop Penetration Time

The Water Drop Penetration Time test (Bachmann et al., 2003) involves recording the time taken for drops of water to infiltrate. This study attempts to try two modified versions of this test to determine a simple, practical method of water repellency intensity testing - the Mini Disk Infiltrometer (MDI), which was tested in the field and the lab, and the Spatial Repellency Index (SRI), which was only tested in the field.

3.2.3.3 Mini-Disk Infiltrometer

Mini-Disk Infiltrometers are compact infiltrometers with a porous steel disk at the base, and an adjustable suction tube in a separate chamber at the top (Figure 3-5). The cylinders are marked like graduated cylinders so that the volume of water sucked out the bottom of the tube can be viewed. It is intended to measure the hydraulic conductivity of the soil (Decagon Devices, 2011).

In this case, one measurement was made at each of five random spots within the plot. The bottom chamber was filled with water, and then the upper suction was set at a low 5 mm tension for all measurements. Then the MDI was placed on the soil for one minute, and the total volume of water drawn out of the infiltrometer was recorded. The five measurements per plot were averaged for statistical analyses. This tension is considered a small negative head, where soil draws water into itself, as opposed to conventional, positive head infiltrometers that push water into the soil.

Figure 3-5: A Mini-Disk Infiltrometer in the field. The top chamber is adjustable for different tensions

3.2.3.4 Spatial Repellency Index

This simple field test is intended to give an estimate of the spatial extent of the water repellent soils (Bachmann et al., 2003; Dekker et al., 1999; Doerr et al., 2006). A small amount of water was drizzled from a squirt bottle along a very shallow (5 mm deep) trench within the plot (Figure 3-6). The purpose of the trench was to stop the water droplets at the surface from rolling down the slope. The percentage of the length of trench that was totally wettable, partly wettable or totally water repellent was estimated. The definition of "partly wettable" was that the water drop would not be immediately adsorbed onto the soil. "Totally water repellent" meant that the water drop remained intact on the surface for more than 60 seconds.

To analyze these measurements, the three classes were given a weight of 1 for totally wettable, 5 for partly wettable and 10 for totally water repellent. Then the percentage of each class was multiplied by the weight and summed for a unitless, numerical value for repellency.

Figure 3-6: Water being dribbled from a squeeze bottle along a shallow 'trench' across the slope to determine the Spatial Repellency Index

3.2.3.5 Soil sampling

Composite soil samples were taken from each transect, air dried for 48 h and then oven dried at 60° C for repellency testing in the lab.

3.2.4 Laboratory tests

3.2.4.1 Mini-Disk Infiltrometer

The sieved, air dried and oven dried (at 60 ºC for 48 h) soil was placed carefully in a 25 cm round aluminum pan. The layer of soil was >35 mm deep, so that the bottom and sides of the pan would not interfere with the measurement.

The tests were repeated five times on the dried samples, and the average measurement used for analysis. The samples had to be re-dried twice because there was only enough soil to take two measurements at the same time. After re-drying, the samples were crushed to break up any aggregates that had formed from the previous wetting.

3.2.4.2 Concentration of Ethanol Drop

The laboratory ethanol measurement was determined just once on the composite soil samples, using the same technique with increasing concentrations as was done in the field.

3.2.4.3 Spatial Repellency Index

The Spatial Repellency Index was not used in the laboratory as it is inappropriate for small and disturbed samples.

3.3 Soil properties

Subsamples of the air dried soils used in the laboratory tests were taken to the UBC Okanagan Soil lab, where two methods of particle size analysis were applied to determine the specific surface area: the sieve method for sand and the hydrometer method for sand, silt and clay fractions.

Dried, crushed composite samples were sieved through screens of decreasing mesh size (2, 0.5, 0.25, 0.106 and 0.053 mm) to determine the sand fraction, while the hydrometer method was used to determine the sand, silt, and clay fractions (Gee & Bauder, 1986,Kettler et al., 2001).

Specific surface area (SSA) was calculated using the following from Hillel (1971) for soils with particles of sandy or silty texture:

$$A_m = (6/\rho_s)\Sigma(c_i/d_i)$$

where Am is specific surface area, ρs is the assumed particle density of the soil and c is the mass fraction of particles of diameter d. The average diameter of the particle size classes was determined using the sieve data for sand, USDA Soil Texture Classification System (USDA,

1993) for average silt diameter, and the average particle size for illite clay for the clay fraction.

The loss-on-ignition method was used to determine organic matter content (Goldin, 1987). Soil water content was determined by the gravimetric method (Black, 1986). Samples were measured before and after drying at 105°C for 24h.

3.4 Statistical analysis

Data were analyzed as a randomized complete block design with eight blocks, each with three replications of two treatments. The blocks were eight forest fires scattered around southern BC. There were three replications within each fire site, and each was called an 'area'. Each area had one transect per treatment. Treatments were a moderately severe wildfire (occurring a year or two before the sampling) and no obvious recent wildfire. Each transect had five plots, and each plot had five measurements for CED and MRI, and one for SRI. The CED and MRI measurements' mean was used for analyses. One SRI measurement was taken at each plot.

The mean water repellency values obtained using the SRI, MDI and CED methods were analyzed using the general linear model (SAS 9.1, SAS Institute Inc., Cary, NC 2004). A separate multivariable regression model was run for each water repellency method used in the field and laboratory with and without the specific surface area data, as that was only measured on the third plot in each transect.

Multi-variable regression analyses were run with backwards elimination to determine the significant variables for five separate response variables (MDI in the field, MDI in the lab, CED in the field, CED in the lab, and SRI in the field), which were the water repellency measurements for each of five tests. The predictor variables tested were: burning, organic matter content (om), 1/om, moisture content (mc), 1/mc, om × burning, mc × burning and specific surface area (SSA). Variables were selected to test the hypotheses about site characteristics that have been shown to influence water repellency in other areas. Inverses to these variables were included in order to see if they increased the hyperbolic model fit. Interactions between burning and moisture content and burning and organic matter were tested to assess the effects of the treatment. The regression analysis was done by putting all possible explanatory variables in the model, and then iteratively removing the least useful by backward elimination (using the Stepwise procedure in the SAS 9.1 software from SAS Institute Inc., Cary, NC, 2004). Fit was tested with the F-test after each variable was removed. Separate regression models were developed for each of the measures of repellency measured in both the field and laboratory. All variables left in the model were significant at the 0.1 level.

One- and two- way ANOVA was performed for the three tests (MDI, CED and SRI) in the field and lab for the treatment (burning) and for BEC zones.

Water repellency was tested according to field measurements of undisturbed soil at ambient wetness, as opposed to measurement of air-dried, sieved soils under standardized conditions in the lab. Total organic matter, gravimetric water content (percent by mass) and specific surface area (as a numerical indication of soil texture) were also variables in the modeling. Site characteristics of biogeoclimatic zone, primary forest cover type and aspect (Table 3-1) were included as additional categorical variables to increase model fit. Burning was assigned dummy values of 1 for burned and 0 for unburned.

3.5 Results

3.5.1 Correlations for all treatments and factors

MDI was significantly ($p < 0.05$) correlated with CED (Table 3-2), organic matter, moisture content and elevation. CED was significantly correlated with MDI, SRI, organic matter, slope and elevation, but not moisture content. SRI was correlated with CED but not correlated with MDI.

Negative correlations were expected between MDI and CED since water repellency was indicated by lower MDI readings and higher CED results. SSA was an indicator of water repellency when the SRI test was used (shows as NS in Table 3-2), but it was not significantly correlated to the water repellency results from the other tests in the field.

Table 3-2: The significant simple linear Pearson correlation coefficients between the variables measured in the field. Significance levels (p) of the correlations are given in parenthesis and indicate the probability (P) of a type-I error.

FIELD	CED	SRI	Organic Matter	Moisture content	SSA	Slope	Elevation
Mini disk infiltrometer	-0.49 (<0.05)	-0.37 (>0.05) NS	-0.24 (< 0.05)	-0.24 (< 0.05)	-0.02 (>0.05) NS	-0.10 (>0.05) NS	-0.36 (p < 0.05)
CED	-	0.65 (>0.05) NS	0.24 (< 0.05)	-0.06 (>0.05) NS	0.26 (>0.05) NS	0.13 (< 0.05)	0.45 (p <0.05)
SRI	0.66 (< 0.05)	-	0.09 (>0.05) NS	-0.40 (< 0.05)	-0.23 (>0.05) NS	-0.10 (>0.05) NS	0.02 (>0.05) NS

Any p value <0.05 is significant. n= 239, NS= Not significant.

Repeating these tests on the dried and sieved soils under laboratory conditions changed the correlations. Table 3-3 shows the results of tests performed in the laboratory for MDI and CED (SRI was not tested in the lab). MDI was significantly correlated with CED, slope and elevation. CED was correlated with MDI, organic matter and elevation. Neither test correlated with the field moisture content of the samples or with specific surface area.

Table 3-3: The significant simple linear Pearson correlation coefficients between the variables measured in the lab.

LAB	CED	SRI	Organic Matter	Slope	Elevation
Mini disk infiltrometer (p>r)	-0.73 (<0.01)	0.09 (0.05) NS	-0.05 (0.42) NS	-0.16 (0.01)	-0.45 (<0.01)
CED (p>r)	-	-0.07 (0.05) NS	0.26 (<0.01)	0.01 (0.85) NS	0.50 (<0.01)
Slope (p<r)	-	-0.09 (0.05) NS	-0.0 (0.99) NS	-	0.20022 (<0.01)

Significance levels of the correlations are given in parenthesis and indicate the probability (P) of a type-I error. n=30, NS = Not Significant

MDI water repellency was not correlated with organic matter or aspect in the laboratory or with slope or aspect in the field. Because it was correlated with organic matter in the field but not in the lab, there may have been an effect of the drying of the soil samples in reducing the water repellency measured with this method (mean water repellency in the laboratory was lower than water repellency in the field on the same sample- see Figure 2-4).

Elevation is correlated with both tests in the field and the lab. Kuskonook was the fire with the highest mean repellency (e.g. lowest MDI measurement and highest CED) and had the highest elevation (approximately 2,000 m.a.s.l.).

For the CED, field measurements were significantly correlated with organic matter content, slope and elevation. Note that elevation and slope were also correlated. In contrast to the laboratory MDI results, laboratory CED water repellency results were significantly positively correlated with organic matter content indicating that soils with a higher organic matter content were more repellent.

The results of the ANOVA tables are given in the following sections, and the ANOVA tables themselves are included as Appendix B. Note that even with numerous power transformations, some of the data did not meet the assumptions for normal distribution.

3.5.2 Test of treatment: burning

When comparing the MDI results for burned sites against MDI results for unburned sites in each fire measured in the field, I found no clear relationship between burned and unburned results on the same sites (Figure 3-7).

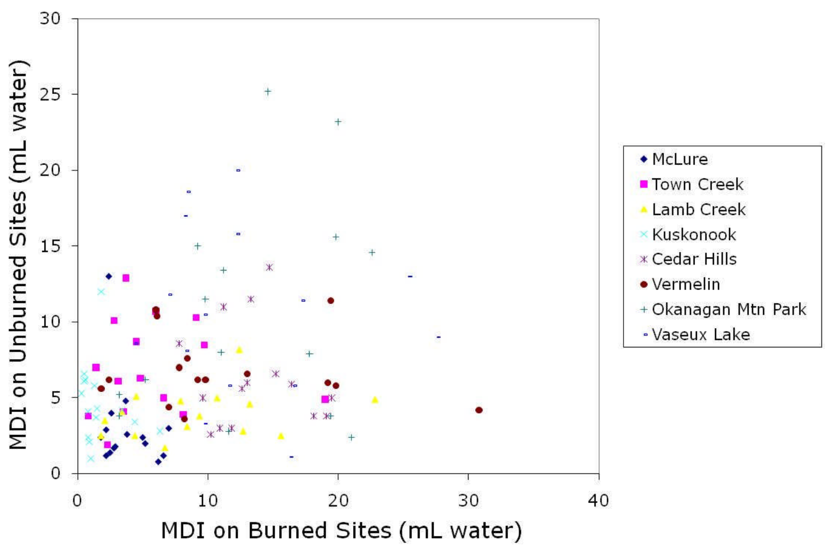


Figure 3-7: I*n situ* Mini-Disk Infiltrometer results for burned and unburned sites at each area

MDI water repellency measurements in the field showed slightly higher infiltration on the burned sites than on the unburned sites at all of the fires, except Kuskonook (Figure 3-8). These results for the fires aside from Kuskonook were not as expected, as literature suggests that burning would decrease infiltration. There were significant differences in MDI results between burned and unburned in the Lamb Creek ($p = 0.002$) Kuskonook ($p = 0.0003$) and Cedar Hills ($p < 0.0001$) fire sites (also see ANOVA tables in Appendix B).

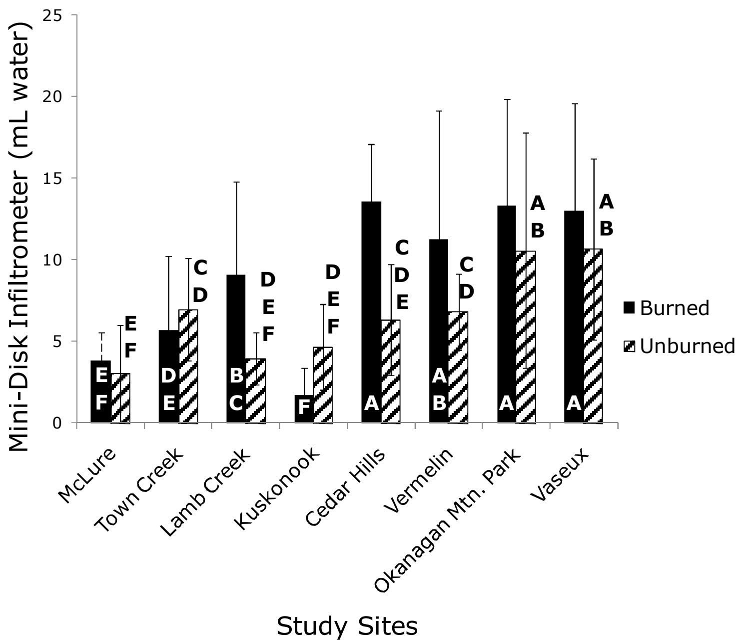


Figure 3-8: Mean Mini-Disk Infiltrometer on burned and unburned transects for field measurements. Error bars represent one standard deviation (n=15). Columns not labeled by the same letter are significantly different using ANOVA.

The CED test did not result in a discernable pattern when compared between burned and unburned transects in the field at each fire area (Figure 3-9).

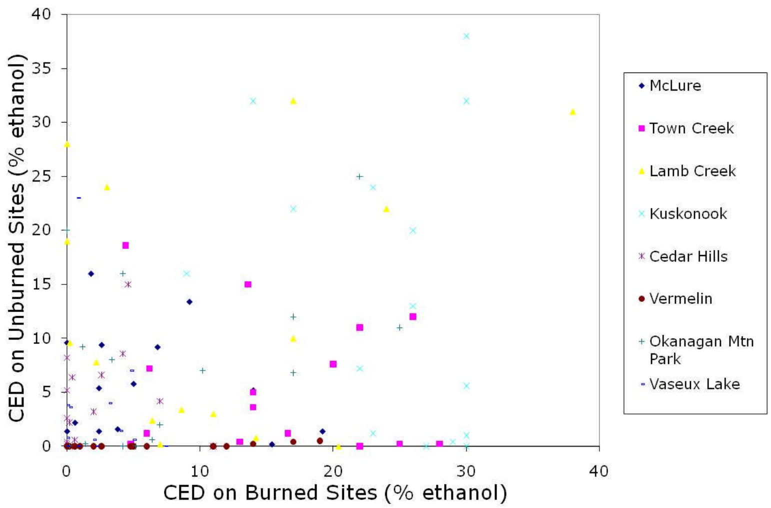


Figure 3-9: *In situ* Concentration of Ethanol Drop on burned and unburned sites at each area

CED measurements also showed large standard deviations in water repellency in the field (Figure 3-10). There were significant differences in water repellency using the CED measurements between burned and unburned sites for the Town Creek ($p = 0.0003$), Kuskonook ($p = 0.0061$), and Vermelin ($p <0.0001$) fires (also see ANOVA tables in Appendix B).

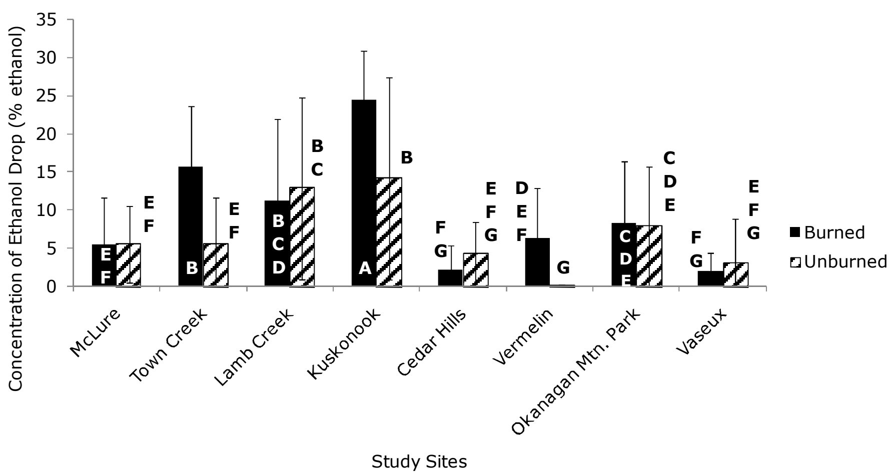


Figure 3-10: Mean Concentration of Ethanol Drop test on burned and unburned transects for field measurements. Error bars represent one standard deviation (n=15). Columns not labeled by the same letter are significantly different using ANOVA.

When comparing SRI on burned and unburned transects in the field (Figure 3.11), the burned areas generally had higher water repellency than unburned fires. Kuskonook's burned sites had significantly higher SRI results than any other area. Vermelin's unburned site showed the lowest SRI, which was similar to the results of the MDI and CED tests (Figure 2-5 in Chapter 2). Note that higher SRI indicates higher repellency. ANOVA analysis showed significant differences between different fires (also see tables in Appendix B).

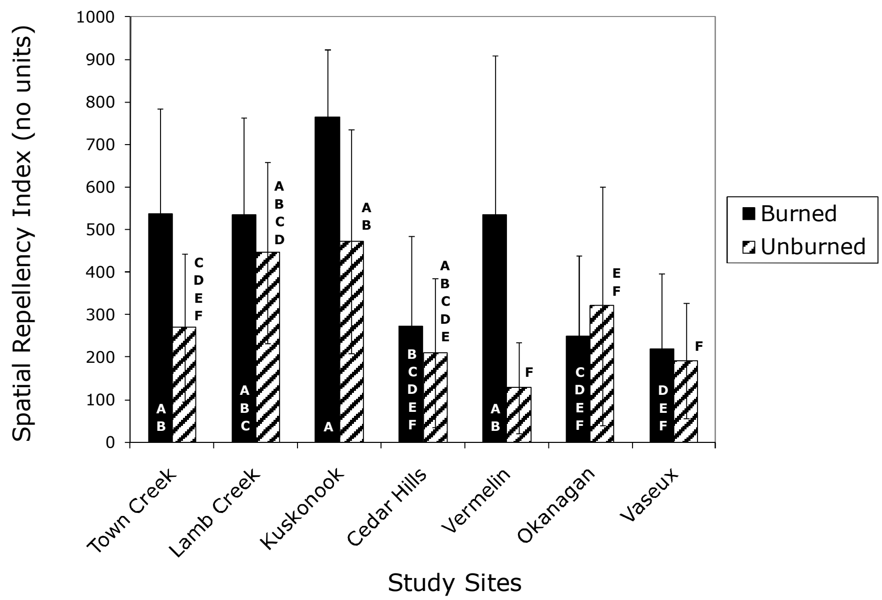


Figure 3-11: Mean Spatial Repellency Index on burned and unburned transects for the 7 fires where SRI was measured. Error bars represent one standard deviation (n=15). Columns not labeled by the same letter are significantly different using ANOVA.

The Okanagan Mountain Park and Vaseux Lake fire sites again showed the lowest repellency measurements. These two sites are from the geographical areas with the hottest July temperatures (Table 3-1). This consistently high heat may affect organic matter in how it decomposes and therefore the sites are not exhibiting the same levels of water repellency as sites with lower maximum summer temperatures.

3.5.3 Factors

Organic matter, moisture content and specific surface area were analyzed to see if they could be used as predictors for the presence and degree of soil water repellency.

3.5.3.1 Organic matter

CED compared to organic matter for all field measurements did show a significant correlation (0.24, Table 3-2). Figure 3-12 shows this relationship for burned and unburned plots. Note that higher CED is an indication of higher water repellency. Generally, we did not find enough evidence to suggest that organic matter is a very good indicator of the presence or degree of soil water repellency when measured with the CED test. Note that CED values of zero indicate that the soil was completely wettable. While it appears that there is slightly less scatter in the burned results than the unburned results, the CED was not strongly related in either treatment.

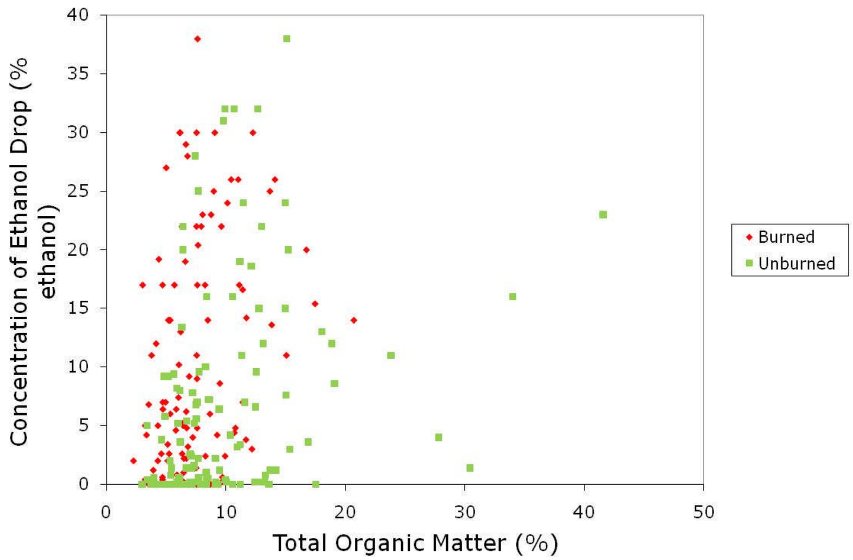


Figure 3-12: Concentration of Ethanol Drop results for field tests of water repellency compared to total soil organic matter

When water repellency was measured with CED in the lab, we also saw a weak but significant correlation (r^2= 0.26 between CED and organic matter in the soil (Figure 3-13). As organic matter content increased, the water repellency actually decreased (high CED indicates repellency).

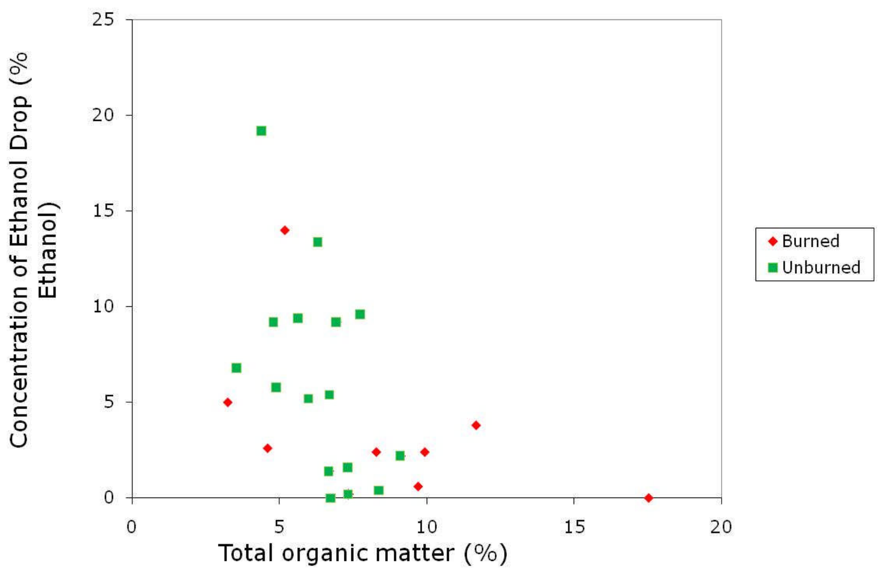


Figure 3-13: Concentration of Ethanol Drop results for laboratory tests of water repellency compared to total soil organic matter

We saw in Table 3-2 above that there was a significant, if low, negative correlation (-0.24) between MDI results and soil organic matter in the field. Figure 3-14 below shows this relationship for the burned and unburned plots in the field. As with the CED test, there was a weak indication that organic matter is useful to predict soil water repellency when measured with the MDI test.

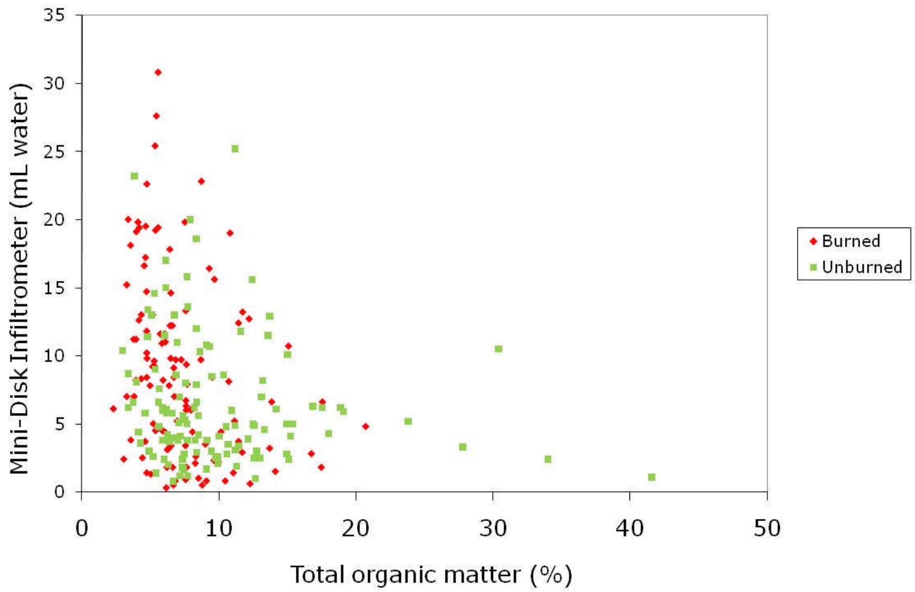


Figure 3-14: Mini-Disk Infiltrometer results for field tests of water repellency compared to total soil organic matter

In the lab, the relationship of water repellency measured with MDI and organic matter was not significant (Figure 3-15).

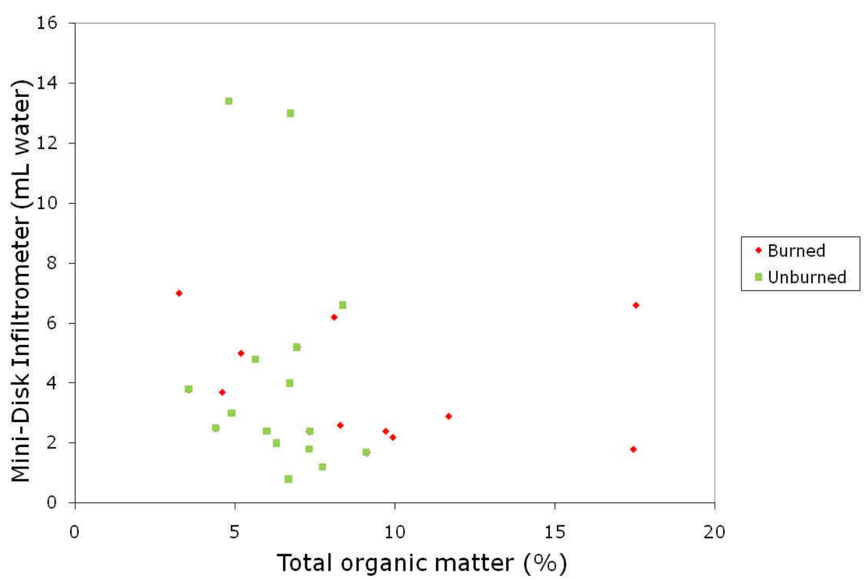


Figure 3-15-: Mini-Disk Infiltrometer results for laboratory tests of water repellency compared to total soil organic matter

SRI was only tested in the field, and did not show a significant correlation with organic matter (Figure 3-16), indicating that testing water repellency is not related to any of the organic matter content levels sampled.

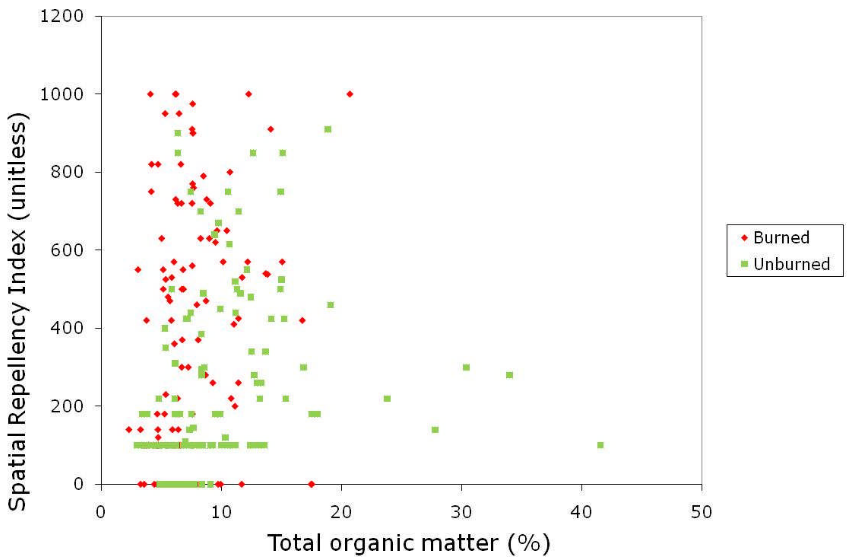


Figure 3-16: Spatial Repellency Index results for field tests of water repellency related to total soil organic matter

3.5.3.2 Soil water content

CED tests in the field indicated no relationship with soil water content. For a broad range of soil wetness, both burned and unburned soils were capable of being highly repellent as indicated by high CED values (Figure 3-17). There is no indication that beyond a certain threshold wetness, soils will be more wettable.

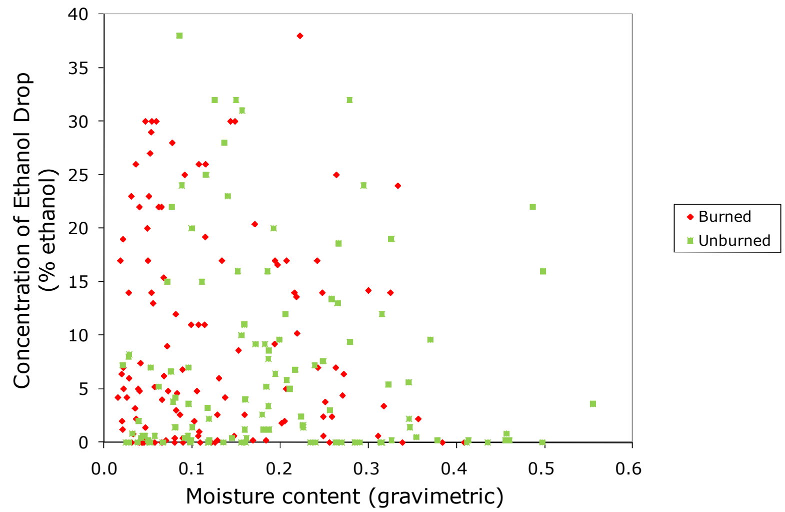


Figure 3-17: Concentration of Ethanol Drop results for field tests of water repellency compared to ambient moisture content

There was a significant relationship between water repellency tests in the field with the MDI method and soil moisture content. Their significant correlation (-0.24, table 3-2) indicates that the higher the moisture content, the lower the water repellency. We expected to see this in soils that are not hydrophobic. There was no significant difference between unburned and burned soils although wetter soils did not show any high MDI values (Figure 3-18).

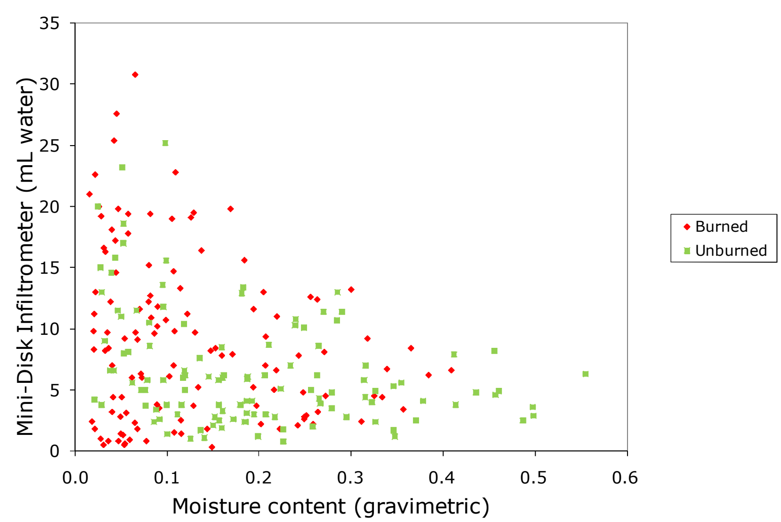


Figure 3-18: Mini-Disk Infiltrometer and soil moisture content in the field

Similar to MDI (Figure 3-18), there was no significant difference in SRI between burned and unburned soils when compared to moisture content, although there was a weak tendency for drier soils to have higher repellency (Figure 3-19) The zero SRI values indicates no water repellency found with this method at those plots. Note that SRI was only measured in the field and was not measured at the McLure Fire.

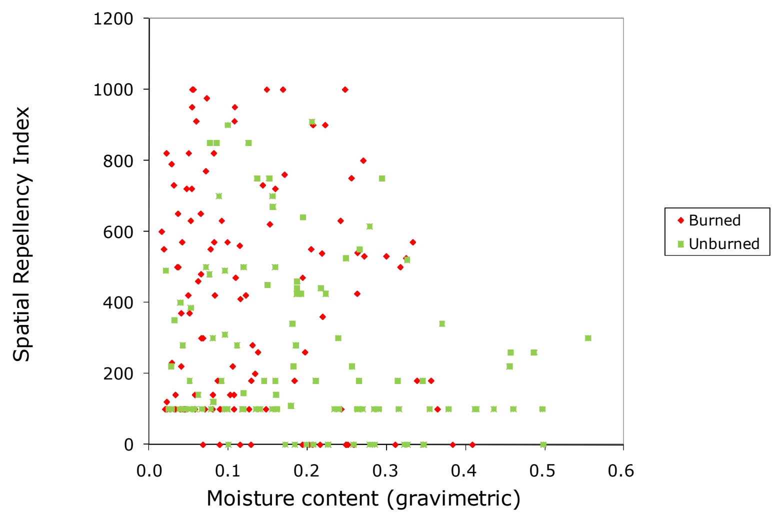


Figure 3-19: Spatial Repellency Index for all field samples plotted against the soil moisture content at the time of measurement

3.5.3.3 Specific surface area

Water repellency was not significantly related to specific surface area (SSA) when measured with CED in either the field (Figure 3-20) or laboratory (Figure 3-21).

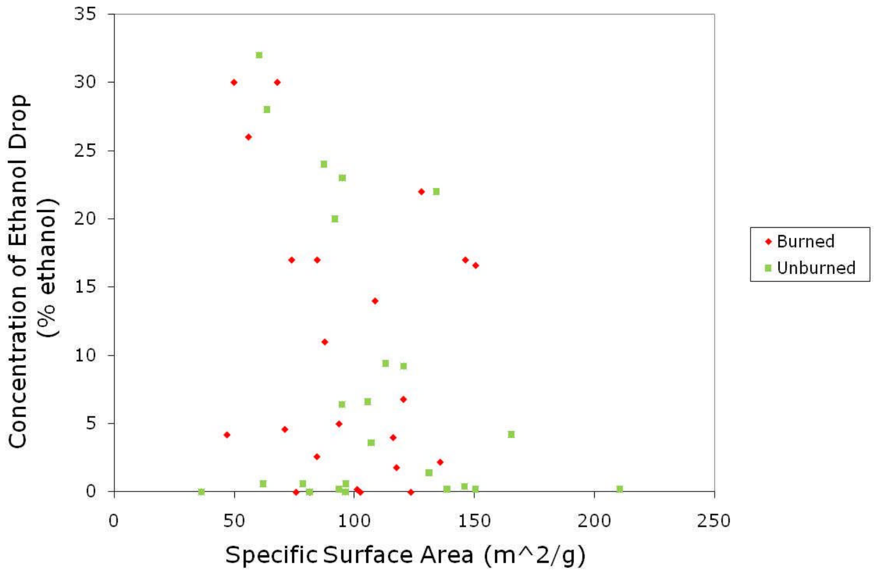


Figure 3-20: Concentration of Ethanol Drop results for field tests of water repellency compared to specific surface area

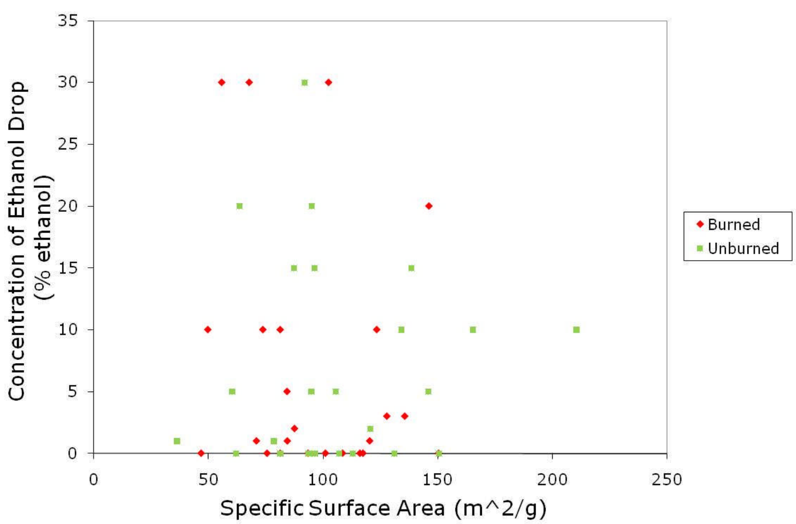


Figure 3-21: Concentration of Ethanol Drop results for laboratory tests of water repellency compared to specific surface area

Similar to the CED measurements, soil texture (measured by SSA) does little to explain the variation in water repellency measured with the MDI test in the field (Figure 3-22) or the laboratory (Figure 3-23).

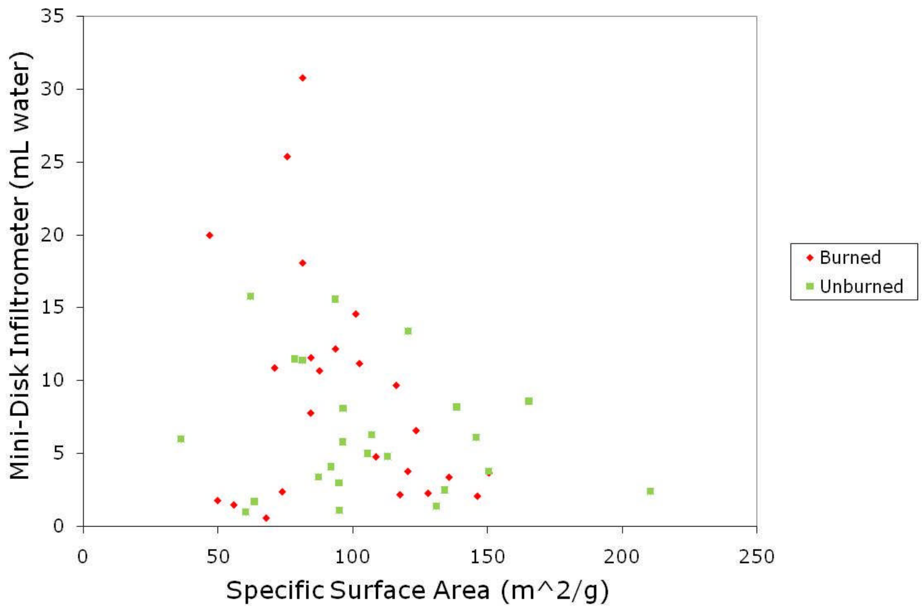


Figure 3-22: Mini-Disk Infiltrometer and specific surface area measured in the field

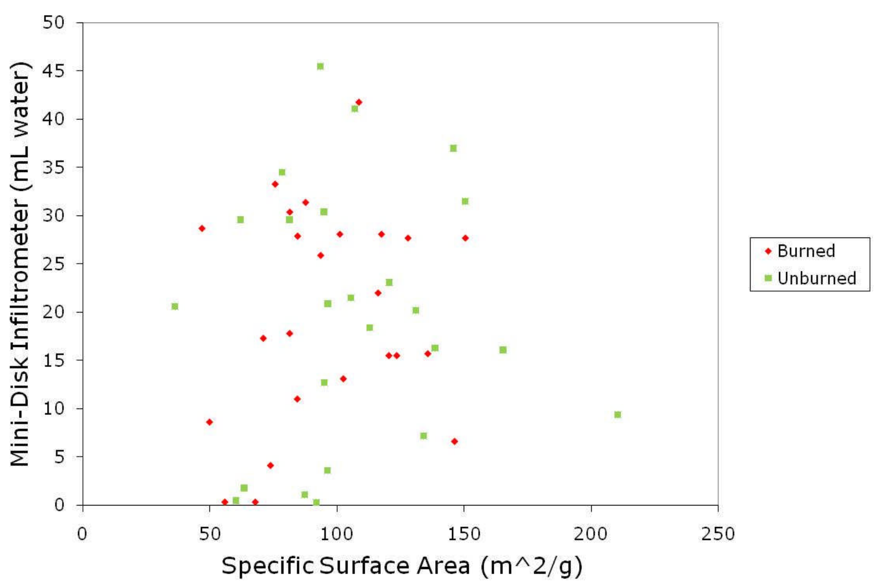


Figure 3-23: Mini-Disk Infiltrometer and specific surface area measured in the lab

Water repellency measured with the SRI method was significantly negatively correlated (Pearson's correlation coefficient of -0.69, p <0.05) to the SSA if the SRI values of 100 (e.g., those with no evidence of water repellency) are removed (Figure 3-24). This was as expected, with soils of larger SSA and smaller particles having less incidence of soil water repellency in studies such as Harper & Gilkes, 1994) and McKissock et al., (2003).

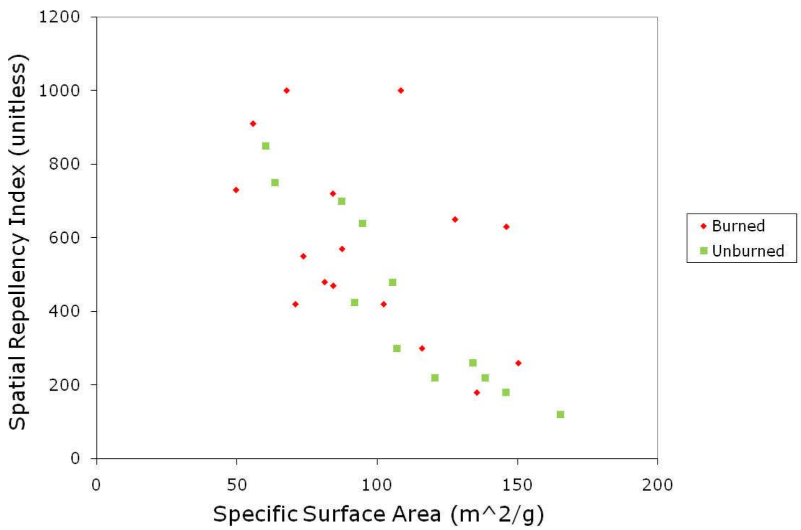


Figure 3-24: Spatial Repellency Index and specific surface area (only measured in the field). Samples with no repellency (SRI = 100) have been removed for this figure.

3.6 Multi-variable regression analysis

Multi-variable regression analyses were run with backwards elimination to determine whether or not water repellency could be accurately predicted from the predictor variables measured. Water repellency was assessed using MDI in the field, MDI in the lab, CED in the field, CED in the lab, and SRI in the field. The potential predictor variables tested were: occurrence or absence of burning, organic matter content (om), 1/om, moisture content (mc), 1/mc, om * burning, mc * burning and specific surface area (SSA). Variables were included based on site characteristics that have been shown to influence water repellency in other areas. Inverses to these variables were included in order to see if they increased the hyperbolic model fit. Interactions between burning and moisture content and burning and organic matter were tested to assess the effects of the treatment. The regression analysis was done by putting all possible explanatory variables in the model, and then iteratively removing the least useful by backward elimination (using the Stepwise procedure in the SAS 9.1 software from SAS Institute Inc., Cary, NC, USA, 2004). Separate regression models were developed for each of the measures of repellency measured in both the field and laboratory. All variables left in the model were significant at the 0.1 level.

In all of these models where factors were significant, there was no consistency in models for burning vs. not burning and laboratory vs. *in situ* conditions. Burning was significant for all of the tests with the MDI, and for SRI, which also happened to be the model with the highest explanation of variance when run without the SSA texture data. Burning was not a good predictor of water repellency in the CED tests (Table 3-4) until I added the categorical variables and all of the tests performed in the field were significant (Table 3-5). Organic matter itself was only significant in two of these models (MDI field and CED lab), but its inverse was significant in six out of the ten models. This means that the more the amount of organic matter decreased, more of the variance was explained.

Moisture content and its inverse were significant in the model with the highest explanation of variance (SRI field) and the CED field model, but were not significant in the other eight models.

Specific Surface Area was significant in 3 of the 5 models. It was not significant when testing water repellency with the MDI method in the field or the CED method in the lab. It was significant when testing water repellency in the field with either the CED or SRI method.

Table 3-4: Multiple regression models with coefficients or "parameter estimates" for significant predictor variables (shaded boxes).

Dependent variable	Burning	Organic matter	1/om	moisture content	1/mc	om* burning	Mc* Burning	SSA	R^2	Root MSE (SE_e)
MDI Field	2.02	-0.18						N/a	0.41	4.76
MDI Field*	6.79						-29.16		0.16	6.18
MDI Lab	4.73		-35.24			-0.50		N/a	0.04	8.02
MDI Lab*	0.65		-0.77					-0.09	0.03	11.58
CED Field				-21.47	-0.30			N/a	0.17	8.72

Dependent variable	Burning	Organic matter	1/om	moisture content	1/mc	om* burning	Mc* Burning	SSA	R^2	Root MSE (SE_e)
CED Field*			-60.75					-0.1	0.24	9.14
CED Laboratory	4.76		-35.24			-0.50		N/a	0.04	8.02
CED Lab*		0.42							0.09	8.95
SRI Field	173.70		-864.6	-623.2	-4.56			N/a	0.52	202.56
SRI Field*			-1300			26.48		-2.93	0.43	225.5

(Significant variables are indicated by a shaded box. Note that a "*" beside the Dependent variable indicates that the model was run with a reduced data set to consider the specific surface area (texture) measurements, which were only determined for every third plot in the transects. Consequently, texture (as SSA) was not considered in models without the * symbol.)

Including the categorical variables increased the model fit. Table 3-5 shows the significant factors when modeled using the same backwards elimination regression described above. Shaded boxes indicate significant coefficients. For BEC, primary tree species and aspect, the table is shaded if at least one of the many variables in that category were significant. After introducing dummy variables to account for the BEC, FC and Aspect, the R^2 for the regression model for "CED in the lab" increased from 0.045 to 0.66. A similarly large change in explanation of variance (R^2 increased from 0.21 to 0.51) was recorded for SRI. Also, with these additional categorical variables in the models, burning became a significant predictor in all of the field models. The best model for predicting water repellency (based on R^2) was in the laboratory tests for MDI and CED where burning was not significant. The dummy variable "BEC" (biogeoclimatic zone) was significant in all models, and organic matter significant in all but the SRI field models. At least one aspect class also turned out to be significant in explaining the most variance.

Table 3-5: Multiple regression models including the categorical variables BEC zone, primary forest cover tree species and aspect with significant variables shaded

Dependent variable	**Burning**	**organic matter**	**1/om**	**moisture content**	**1/mc**	**BEC**	1° tree species	**Aspect**	**R^2**	**Root MSE**
MDI Field	1.97	-0.20							0.36	4.85
MDI Lab		-0.50	-32.67	n/a	n/a				0.61	7.80
CED Field	3.03	0.36		-7.76					0.46	7.40
CED Laboratory		0.54	24.30	n/a	n/a				0.66	5.11
SRI Field	165.66		-1,059.1	-438.1					0.51	205.0

Separate regressions were performed for each combination of dummy variables. For presentation purposes, since there were 14 possible BEC zone categories, 10 forest cover primary tree species categories and 4 aspects, the cell was shaded if at least one of those variables was significant.

3.7 Discussion

At all of the fire sites, at least some unburned soils were repellent and at least some burned soils were wettable. ANOVA tests showed significant differences between burned and unburned soils at some of the fires, but not at others. The repellency in the unburned soils may be due to the inherently water repellent nature of the organic matter in the soil. These findings are consistent with (Doerr et al., 2009), who tested various soil variables across Colorado, Montana, Idaho, Wyoming, Oregon and Utah in order to assess water repellency in unburned soils. They found that 75% of the soils exhibited some degree of ‘natural background’ water repellency. Site conditions such as summer temperatures and elevation seem to have an effect on water repellency, likely through their effects on the organic matter in the soil. Areas with hotter maximum mean summer temperatures had lower water repellency in both unburned and burned sites.

In all of these models where factors were significant, there was no consistency between burned vs. not burned treatments and laboratory vs. *in situ* conditions. Burning showed a significant effect on water repellency as determined by the MDI and SRI tests Note that the SRI method had the highest explanation of variance when run without the SSA texture data. Burning was not a good predictor of water repellency determined by the CED test (Table 3-4) until I added the categorical variables and all of the tests performed in the field were significant (Table 3-5). This may be because the sampling was done one to two years after the wildfire had burned, and the effects of that fire did not persist. MacDonald & Huffman (2004) found that hydrophobicity after fire decreased to the point where it was statistically non-detectable by 12 months after fire in Colorado.

Organic matter itself was only significant in a small number of these models until I added the categorical variables of BEC, primary forest cover and aspect. This may be because when I analyzed the results by models for each BEC zone, the sites were compared against each other more explicitly, instead of being analyzed together. The maximum mean temperature for July is lowest for Kuskonook and highest for Okanagan Mountain Park and Vaseux Lake (Table 3-1). The hot summer temperatures may destroy or change the orientation of the organic matter on the latter two sites, while cooler temperatures at Kuskonook and Lamb Creek preserve the water repellent orientation of the organic compounds.

While significant in some cases, the weak relationship between total organic matter and soil water repellency (e.g. Figure 3-14) is similar to other published work. Some studies, such as those done by Dekker & Ritsema (1994a) and Doerr et al., (2005), found no correlation between total organic matter and water repellency. Organic matter was only weakly linked to water repellency when using the Critical Surface Tension (CST) test in a study by Scott (2000). The persistence of water repellency also had poor correlation to organic matter in Australia (Harper et al 2000), the Netherlands (Dekker & Ritsema, 1994a) and Germany (Buczko & Bens, 2006).

As with organic matter, soil water content, and specific surface area did not prove to be reliable indicators of soil water repellency on the sites in my study. This was true for both the burned and unburned treatments. This was similar to findings of Rodriguez (2007) who also found no relationship between water content and water repellency in forest soils. He speculated that this was due to the type and amount of organic matter, since he did find a significant negative relationship between water content and water repellency in soils under maize or grasses. De Jong et al. (1999) found a correlation between water content and water repellency, but speculated that this was actually an effect of temperature. Higher temperatures dried the soils and reoriented the organic compounds. Robichaud & Hungerford (2000) also found that coarser soils did not exhibit higher water repellency in a laboratory analysis of four northern Rocky Mountain soils.

Elevation was likely to have increased model fit because the Kuskonook fire (which had higher repellency measurements with all three tests in the field and both tests in the lab) had an average elevation 200 m higher than the next highest site (i.e., Lamb Creek) and 680 m higher than the average of all of the sites. Barrett & Slaymaker (1989) also found water repellency at high elevations on unburned sites with a high organic matter accumulation. They did not include sites at lower elevations into their study. Aspect was likely effective in strengthening the model because the aspects that face the sun have hotter, drier soils and are more likely to burn in a fire than cooler, moister soils on northern aspects.

3.8 Conclusions

There is no simple way of predicting where water repellent soils will be found. All of the multiple regression models carried in my study, regardless of inclusion of the categorical dummy variables, indicate that there is no consistent “best” model or, in other words, one set of consistent predictors of water repellency risk. Although the models developed on laboratory data had higher predictive value, there was still very low explained variance. None of these factors of burning, organic matter, aspect, elevation, primary tree cover, moisture content or specific surface area can be looked at in isolation when assessing a soils’ potential for water repellency. Burning was a significant factor when measured in the field; however the drying and sieving involved in the laboratory tests seem to erase that significance.
In this study, I wanted to determine whether burning increased the presence of water repellency across the southern BC. Instead, I found that burning alone is not an indicator of soil water repellency, at least not one to two years after wildfire. ANOVA tests on the data showed inconsistent effects of burning for all three tests. This indicates a high instance of ‘natural background’ water repellency in unburned soils. These hydrophobic soils may be held in place by the existing vegetation, and then when fire removes the vegetation there is a higher risk of mass movement.

Contrary to the findings of other studies, total soil organic matter content alone was not a good predictor for the presence of water repellency. This warrants further exploration focusing on the type of organic matter and its effects on water repellency in these particular soils.

Soil water content alone was also not a valid indicator of soil water repellency on the study sites. Soil texture (as SSA) can be used to predict at least weak soil water repellency if using the MDI method in the lab, the CED method in the field or the SRI method in the field.

The findings from this study show that burning, organic matter, texture and ambient moisture content are not useful for predicting water repellency in soils in southern British Columbia one or two years after a fire. The study did show that water repellency exists in soils throughout the province. Soil water repellency should be a consideration in hydrological planning and wildfire rehabilitation efforts.

Chapter 4: Overall conclusions

Water repellency was common in unburned and burned soils in the southern BC. This study is unique in that there have been very few studies testing the presence of soil water repellency in the southern Interior, and very few studies globally that compare the MDI, CED and SRI tests, and even fewer that compare field to laboratory conditions.

I was able to identify sites with high and low water repellency. None of the variables tested (i.e., organic matter, soil water content, and texture) showed that they can be used in isolation to predict the presence or degree of water repellency. The MDI, CED and SRI tests did show that any of them are valid to test for the presence of water repellency.

4.1 Results of hypotheses testing

4.1.1 Various methods of testing for soil water repellency

1. Modified CED tests will show similar trends on the same soil in the field and after drying and sieving in the lab. **Not Rejected**

The laboratory and field results were moderately correlated for the CED tests. The field measurements resulted in slightly higher repellency than laboratory measurements on the same soil. This is likely due to the breakdown of organic hydrophobic structures during the drying and sieving processes. This was similar to the findings of Dekker et al., (2001), who found that water repellency was more severe in the field than in the laboratory on the same soils when they used the WDPT method.

2. Field MDI tests will show similar ranges of water repellency results in the field as in the lab. **Not Rejected**

The MDI results obtained in the laboratory were correlated to those obtained in the field. Again, there was a trend for higher repellency in the field than on the same soils after drying and sieving in the lab.

3. Field CED and field MDI tests will show similar trends of water repellency results for the same sites. **Not Rejected**

The strong, negative relationship between the field data obtained by the CED and MDI tests was observed. The negative relationship was due to low MDI and high CED readings indicating higher water repellency. The multiple regression models were completely different for these two tests, with burning being a significant factor in water repellency for MDI, but not for CED.

4. Laboratory CED and laboratory MDI tests will show similar patterns of water repellency results for the same sites. **Not Rejected**

The laboratory data obtained by MDI and CED tests had similar patterns. Burning increased the soil water repellency when samples were tested with either method. Both the MDI and CED showed higher repellency in the field than the laboratory, which is likely due to the drying and sieving used to prepare samples.

5. When used in the field, a modified Water Drop Penetration Test (WDPT), will show the same trends of water repellency as the CED and MDI tests. **Rejected**

I found that the Spatial Repellency Index (SRI; a simplified WDPT test) did not give similar results to the MDI test. Lewis et al. (2005) found a significant correlation (r^2=0.64) between the MDI and WDPT on the Hayman fire in Colorado. Buczko & Bens (2006) found a significant relationship between the WDPT and Critical Surface Tension (which is based on the same principles as the CED test), but the strength of the relationship depended on the soil depth and season. My SRI test results did show similar indications of the presence of water repellency as the CED tests, and similar trends in the presence of water repellency (e.g. all showed the highest repellency on the Kuskonook fire).

4.1.2 Predictive indicators

Environmental factors that have been found to affect water repellency in similar studies in other regions can be used to predict the presence of post-fire water repellency in BC:

6. Wildfire that is severe enough to burn the duff layer will increase the existence of water repellency in soils. **Rejected**

The burned sites did not show more instances of soil water repellency than the paired unburned sites at the surface of the mineral soil. If wildfire increases the existence of water repellency in forest soils of the southern BC, it does not persist at the mineral soil surface one or two years later. This was similar to other work by Huffman et al. (2001) in Colorado and Doerr et al. (2006). This may be because of the relatively high levels of 'natural' or 'background' water repellency that we saw in the unburned sites. MacDonald & Huffman (2004) found no difference between fire-induced soil water repellency 12 months after a fire in northern Colorado lodgepole pine and ponderosa pine forests.

7. Greater organic matter content in the soil will increase the degree of water repellency in all tests. **Rejected**

I did not find more than a weakly significant positive relationship between total organic matter content and soil water repellency for all tests. Harper et al. (2000) also found that organic matter was not a significant predictor of water repellency with the Water Drop Penetration Time test. Other studies such as Dekker & Ritsema (1994) found that water repellency tests using the Molarity of Ethanol Drop method were negatively related with organic matter. You seem to have found something similar to D & R – higher OM leads to greater wettability – and this is opposite from what you hypothesis states.

8. Drier soils will have higher instances of water repellency. **Rejected**

Soil water content in the field was not a good predictor for soil water repellency. Drying the soil samples in the laboratory reduced water repellency, but that may also have been because of the physical treatment (sieving) of the samples. This was unlike the general assumption that water repellency was related to soil water content as a pointed out by Leighton-Boyce et al. (2005), and that the dried soils would show greater repellency.

9. Soils with greater SSA (i.e., finer textured soils) will have lower incidence of water repellency in all tests. **Rejected**

Specific surface area was correlated with the water repellency measured in the MDI and SRI tests, but not the CED test. The results for MDI and SRI are similar to work by DeBano (1981), who found that coarse soils were more repellent than finer textured soils.

4.2 Strengths and limitations of this research

The methods tested were chosen primarily because of their simplicity. None of the CED, MDI or SRI tests need complicated, cumbersome equipment or extensive training. All of the methods proved to be effective for testing for the presence of water repellency, based on the findings from comparing CED, MDI, and SRI methods in the field and laboratory. The main limitation of these tests is their low precision for testing the degree of water repellency. They are not able to show the exact degree of water repellency like a method that shows precise contact angles. The largest limitation to this research was the lack of data from shortly after the wildfires had occurred. Water repellency may have developed as a result of the fires, but the breakdown of the water repellency had erased the effects of burning as a treatment for this study in the 12-24 months before sampling occurred.

4.3 Other potential sources of error

- Tree identification was a problem because burning removed so much of the identifying factors. In some areas all of the branches were burned off of the stems. Therefore, the primary forest cover sometimes had to be a 'best guess' based on maps and charred tree remains.
- Organic matter measurements may have been distorted by the presence of ash in the samples.
- Texture may have been affected by the fire especially if a rain washed away the fine particles, a soil would look coarser than if it had been measured before a fire or large rain event caused erosion.
- Sites were chosen based on their access rather than randomly. Truly random site selection was impossible because of the inaccurate maps and inability to determine fire severity before seeing the site in person.

4.4 Further research

It would be beneficial to the field of knowledge to assess the qualities of organic matter in soils that exhibit natural background water repellency in the southern BC. Many of the soils in this study exhibited natural background soil water repellency. Further assessments of the relationship between natural background soil water repellency and site factors such as maximum site temperatures, elevation, forest cover and/or vegetation, aspect and soil parent material would also be useful. The relationship of pre-existing water repellency to post-fire water repellency should be examined. This is very important in the southern BC because of the frequency of wildfire and the proximity of many communities to forests with high wildfire hazards. These communities often depend on these forests for their water supply, and are also affected by hydrological events such as debris flows. Wildfire may increase the risk of large debris flows if there is a large rainflow event and the protective forest floor and vegetation have been burned off. This debris flow risk is further amplified if the soil is water repellent.

As some studies have shown, the persistence of water repellency decreases over time. If sites are accessible, it would be interesting to test soils on sites that had burned more recently than the two year period in these studies.

There have been many more studies done under controlled laboratory conditions than in situ. Preparation of soil samples for laboratory analyses changes the water repellency, which does not give a true picture of what is happening in those soils. Studies comparing the effects of different laboratory preparations would be useful for this field of study as well. For example, it would be useful to study the effects of various lower drying temperatures and different sieve sizes or not sieving at all. I would like to see the work continue to study what factors affect water repellency on undisturbed soils in ambient moisture conditions in the field.

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Appendix A: Wildfire information for each of the study areas

8 areas were chosen for this study based on three characteristics: 1) relatively large size, 2) a wildfire in 2003 or 2004 and 3) a broad network of roads throughout. Following is information on each fire, BC Ministry of Forest and Ranges assessment of the effects of the fire on local structures and soil, if available, and dates sampled.

McLure/Barriere
Location: McLure BC, 50 km north of Kamloops on Hwy 5. The forests that were burned are managed by Tolko and there is an extensive, well maintained network of forest access roads.
Date fire reported: July 30, 2003
Size of fire: 26,420ha
Fire weather information[1] for the Sparks Lake weather station on July 30, 2003 were:
FFMC: 97.9
DMC: 226
DC: 899
ISI: 18.2
BUI: 277
FWI: 58

Proximity to developed areas/loss of resources/structures: The entire town of McLure, including the main source of employment (the Tolko mill) was burned, and part of the town of Barriere was also lost.
Dates sampled: July 11-13 2005

Town Creek
Location: North of Lillooet, BC. The fire was visible from town, which was evacuated as a precaution during the fire.
Date of fire start: 18 June 2004
Size of fire: 1,500 ha
Fire weather information: not available

Date of sampling: July 19 & 20, 2005

Lamb Creek
Location: 27km southwest of Cranbrook in the Purcell Mtns, the East Kootenays

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[1] FFMC- fine fuel moisture content
BUI- total fuel available to burn
DC- drought code
ISI- Initial spread index
RH-relative humidity

Date of fire initiation: August 7, 2003
Size of fire: 10, 637 ha
Weather data (Cranbrook Forest Service, August 7, 2003):
FFMC: 81.3
DMC: 132
DC: 892
ISI: 2.7
BUI: 193
FWI: 15.3

Proximity to developed areas/loss of resources/structures: Town of Lumberton evacuated
Landslides after fire: Several small ones noted by foresters and seen in the field.
Date of sampling: July 26 & 27 2005

Kuskonook
Location: East of Kootenay lake, 25 km north of the town of Creston in the Purcell Mtn. range.
Date of fire: Started August 27, 2003
Size of fire: 4,832 ha

Akokli Creek (Nelson) weather station (90 km away from the fire) data showed just 7mm of precipitation in the previous 2 months, and the following fire weather data on August 27:
FFMC: 92.3
DC: 760
ISI: 20.6
BUI: 21.3

Landslides after fire: There were several throughout the burned area a year after the fire, with the largest on the east facing steeper slopes in what was believed to be the initiation zone for the fire.
Dates of sampling: July 28-29 2005

Cedar Hills
Location: East of Falkland, visible from Hwy 99 to Vernon.
Date of fire start: 1 August 2003
Size of fire: 1,600ha
Fire weather information: not available

Proximity to developed areas/loss of resources/structures- fire burned across Highway 97 but there were no reported losses of structures.
Landslides after fire: Yes, on slopes on east end of fire. Luckily only one structure was affected.
Dates of sampling: July 18, 21 and August 9

Vermelin
Location: North of Vermelin Lake, about 50 km north of Barriere

Date of fire: August 7, 2003
Size of fire: 3,981 ha
Fire weather information: not available

Dates of sampling: August 4 & 5, 2005

Okanagan Mountain Park
Location: South of Kelowna on the shore of Okanagan Lake
Date of fire initiation: August 16, 2003
Size of fire: 25, 912ha
Weather from the station in Penticton for August 15, 2003:
Temp: 26.7°C
FFMC: 96.3
ISI: 17.1
FWI: 54.8

There was no precipitation between June 22 and September 13, and the Build-up Index (BUI) had reached 425, which is almost five times the Canadian extreme for this index.
Over 250 houses and several historical railway trestles on the KVR were lost. There were several debris flows that exceeded culvert capacities as a result of this fire.
Dates of sampling: August 10, 11 & 24

Vaseux Lake
Location: East of Vaseux Lake, just south of Okanagan Falls
Date of fire initiation: August 22, 2003
Size of fire: 3300 ha
Fire weather information on August 22, 2003 at Penticton were:
Temp: 26.5°C
FFMC: 94.7
DMC: 328
DC: 1083
ISI: 16.7
BUI: 373
FWI: 55.3

The indices, especially the drought code (DC), were considerably higher than any experienced previously by the stations. The indices indicated that fire initiation would result in rapid spread with difficult control.
A landslide across Hwy 97 occurred after this fire.
Average Elevation of measurements: 882 masl
Dates of sampling: 15-17, 2005

Appendix B: ANOVA tables

Comparing Treatments (T)- burning and not burning at each fire site (F) in the field

Table B-1: Results of ANOVA where variance in CED (square root transformation) was analyzed for treatment (burning, or T) effects and for treatment effects within fire sites (F), measured in the field.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	8	22.32	14.39	Significant
Error	230	1.55		
Corrected Total	238			
Effect tests				
T	1		9.74	Significant
F	7		15.02	Significant

Table B-2: Results of ANOVA where variance in MDI (square root transformation) was analyzed for treatment (burning, or T) effects and for treatment effects within fire sites (F) , measured in the field.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	8	10.08	17.41	Significant
Error	231	0.58		
Corrected Total	239			
Effect tests				
T	1		10.42	Significant
F	7		18.40	Significant

Table B-3: Results of ANOVA where variance in SRI (natural log transformation) was analyzed for treatment (burning, or T) effects and for treatment effects within fire sites (F) , measured in the field.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	7	268,475	6.05	Significant
Error	34	44,342		
Corrected Total	41			
Effect tests				
F	6		5.81	Significant
T	4		7.53	Significant

Comparing Treatments (T) burning and not burning at each fire site (F) in the laboratory

Table B-4: Results of ANOVA where variance in CED (natural log transformation) was analyzed for treatment (burning, or T) effects and for treatment effects within fire sites (F) , measured in the laboratory.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	8	3.73	23.83	Significant
Error	231	0.16		
Corrected Total	239			
Effect tests				
T	1			Significant
F	7			Significant

Table B-5: Results of ANOVA where variance in MDI was analyzed for treatment (burning, or T) effects and for treatment effects within fire sites (F) , measured in the laboratory.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	8	2,002.38	28.62	Significant
Error	231	69.96		
Corrected Total	239			
Effect tests				
T	1		0.03	Not Significant
F	7		32.71	Significant

Tests- for datasets (D) in field and laboratory for each fire (F)

Table B-6: Results of ANOVA where variance in MDI (square root transformation) was analyzed for measuring in the field and laboratory on burned soils.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
D	1	121.78	168.62	Significant
F	7	28.12	38.93	Significant
D*F	7	7.57	10.48	Significant
Total				

Table B-7: Results of ANOVA where variance in MDI (square root transformation) was analyzed for measuring in the field and laboratory on unburned soils.

Source of Variation	d.f.	MS	F	Pr > F
D	1	156.75	170.56	Significant
F	7	21.38	23.27	Significant
D*F	7	8.03	8.74	Significant
Total				

Table B-8: Results of ANOVA where variance in CED (square root transformation) was analyzed for measuring in the field and laboratory on burned soils.

Source of Variation	d.f.	MS	F	Pr > F
D	1	9.51	29.7	Significant
F	7	7.25	22.62	Significant
D*F	7	2.39	7.46	Significant
Total				

Table B-9: Results of ANOVA where variance in CED (square root transformation) was analyzed for measuring in the field and laboratory on unburned soils.

Source of Variation	d.f.	MS	F	Pr > F
D	1	0.03	0.09	Not Significant
F	7	5.39	14.12	Significant
D*F	7	1.99	5.21	Significant
Total				

Table B-10: Results of ANOVA where variance in SRI (square root transformation) was analyzed for measuring in the field on burned soils.

Source of Variation	d.f.	MS	F	Pr > F
Model	6	613,564.20	10.99	Significant
Error	98	55,837.54		
Corrected Total	104			

Table B-11: Results of ANOVA where variance in SRI (square root transformation) was analyzed for measuring in the field on unburned soils.

Source of Variation	**d.f.**	**MS**	**F**	**Pr > F**
Model	6	231.39	6.92	Significant
Error	98	33.46		
Corrected Total	104			