

# WATER REPELLENCY OF TWO FOREST SOILS AFTER BIOCHAR ADDITION

D. S. Page-Dumroese, P. R. Robichaud, R. E. Brown, J. M. Tirocke

**ABSTRACT.** Practical application of black carbon (biochar) to improve forest soil may be limited because biochar is hydrophobic. In a laboratory, we tested the water repellency of biochar application (mixed or surface applied) to two forest soils of varying texture (a granitic coarse-textured Inceptisol and an ash cap fine-textured Andisol) at four different application rates (0, 1, 5, and 10 Mg ha<sup>-1</sup>) and five soil moisture contents (0%, 25%, 50%, 75%, and 100% of saturation). To address the impact of biochar on water infiltration into the soil, we measured soil water repellency using three methods (tension infiltrometer, water drop penetration, and molarity of ethanol). Generally, all three infiltration methods gave similar results. Compared to the unamended coarse-textured Inceptisol at 0% saturation (oven dry), biochar mixed into the soil at the rate of 5 Mg ha<sup>-1</sup> did not result in a significant change ( $p \leq 0.05$ ) in infiltration rate. The fine-textured Andisol soil at 0% saturation did not show a significant change in infiltration at the application rate of 1 Mg ha<sup>-1</sup> when biochar was mixed into the soil. Surface applications of biochar on both soil textures resulted in less water infiltration than the mixing treatments. Our results suggest that biochar decreases infiltration rates less on coarse-textured forest soils as compared to finer-textured soils, and 1 to 5 Mg ha<sup>-1</sup> will likely not detrimentally alter water infiltration rates.

**Keywords.** Biochar, Black carbon, Carbon sequestration, Hydrophobicity, Infiltration rate.

Significant areas of the western U.S. face land management challenges related to wildfire, insect and disease outbreaks, and invasive species. Many of these risks will likely be exacerbated by global climate change (Coleman et al., 2010). Effectively managing forestlands will require treatments that improve ecosystem resilience, minimize wildfire risk, and improve watershed conditions. Currently, forest restoration or rehabilitation treatments involve forest thinning and regeneration harvests that can produce 40 to 60 million dry metric tons of woody biomass per year (McElligott et al., 2011; Buford and Neary, 2010). This material has been largely ignored in the past but is now being considered as a valuable resource for both bioenergy and the pyrolysis byproduct biochar (Spurr and Vaux, 1976). Production of a valuable byproduct (biochar), coupled with new national and international policies that promote large-scale biomass utilization (Abbas et al., 2011), can lead to changes in how forest soils and stands are sustainably managed. Changes in forest hydrologic function, long-term site productivity, and carbon sequestration are critical to address before management activities are considered.

In the western U.S., a majority of the excess woody biomass generated during normal harvest activities (i.e., slash piles) can be used as feedstock for the sustainable production of biofuel and could result in the production of large quantities of the byproduct biochar (Mohan et al., 2006). Biochar is biomass-derived black carbon (C) produced through the pyrolysis process and is analogous to black C naturally found in fire-prone ecosystems in the western U.S. (Deluca and Aplet, 2008). Biochar has been used as a soil amendment in many agricultural systems (Lehmann and Joseph, 2009) and in addition to a long residence time for C sequestration, it can improve soil organic matter, nutrient cycling, and water holding capacity to enhance plant growth (Rondon et al., 2007). Agricultural systems lend themselves to biochar application, where it can be applied and incorporated during soil tillage operations (Page-Dumroese et al., 2009), but forest ecosystems are also prime candidates for soil improvement from biochar additions (Coleman et al., 2010; Page-Dumroese et al., 2009).

Charcoal is a major component of the fire-prone ecosystems of the western U.S. as a result of wildfires or prescribed burns (Certini, 2005). Its composition is highly variable, and the final product is a result of fuel type and moisture content, burn condition and duration, and ambient temperature (Nocentini et al., 2010). On many forest sites, soil infiltration rate changes after burning, and increased burn severity is correlated with decreased water infiltration and increased water repellency (Doerr, et al., 2000; Parsons et al., 2010). Soil texture and the amount of black C on the soil surface are two factors that contribute to the degree of water repellency (Lewis et al., 2006). In burned areas, water that does not permeate the soil becomes runoff, which leads to soil particle detachment and transport, ultimately

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The authors are **Deborah S. Page-Dumroese**, Research Soil Scientist, **Peter R. Robichaud**, ASABE Member, Research Engineer, **Robert E. Brown**, Hydrologist, and **Joanne M. Tirocke**, Biological Science Technician, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho. **Corresponding author:** Deborah S. Page-Dumroese, 1221 S. Main, Moscow, ID 83843; phone: 208-883-2339; e-mail: ddumroese@fs.fed.us.

resulting in erosion of nutrient-rich topsoil (Robichaud and Waldrop, 2000). Biochar, like black C, is made from forest residues and is naturally hydrophobic. However, pyrolysis-created biochar can have particle sizes and physical (e.g., hydrologic) properties that differ from the black C produced during wildfires. The water repellency of biochar is dependent on both the feedstock and the pyrolysis conditions (Kinney et al., 2012). Adding biochar to forest soils may alter the soil hydrology by increasing water holding capacity, decreasing water infiltration, or both (DeBano, 2000; Bacile et al., 2009; Chun et al., 2004). Briggs et al. (2012) observed extreme water repellency (water drop penetration test >2 h) for a freshly produced ponderosa pine (*Pinus ponderosa*) derived charcoal, but older carbon under forest floor layers was less water repellent. Unlike the hydrocarbons created during a fire, where extreme temperature gradients force hydrocarbons into the soil profile (Robichaud et al., 2008), biochar does not coat mineral soil particles but causes water repellency of the soil surface because it is a hydrophobic substance until it is sufficiently wetted. Biochar, coated particles, or charcoal from fire may alter water movement into the soil profile by preventing water infiltration into the mineral soil (DeBano, 2000).

Estimating changes in soil hydrologic processes after biochar additions is important because water-repellent soils have an impact on infiltration rates (Doerr et al., 2000; Robichaud et al., 2008). Past studies have shown increased water retention of biochar-amended agricultural soils (Novak et al., 2009), and some infiltration research has been conducted on naturally occurring black C (Briggs et al., 2012). In addition, there is a large body of work on hydrophobicity and water repellency induced by wildfire (e.g., DeBano, 1981; Doerr et al., 2000). There has been little work on the application of biochar to forest sites, but interest in using biochar is increasing as the pyrolysis of biomass from forest thinnings increases (Coleman et al., 2010). It is critical to understand how biochar may alter soil hydrologic functions on a variety of soil types prior to application (McElligott et al., 2011). Therefore, our primary objective was to conduct a laboratory assessment to evaluate the water repellency of biochar either added to the soil surface or mixed into the mineral soil for both fine and coarse textured soils. Our goal was to assess soil water infiltration rates changes using (1) tension infiltrometer tests (MDI; Lewis et al., 2006; Robichaud et al., 2008), (2) water drop penetration time (WDPT; DeBano, 2000; Letey et al., 2000), and (3) molarity of an ethanol drop (MED; Doerr, 1998) to develop some best application rates and methods for land managers.

## MATERIALS AND METHODS

### SOIL DESCRIPTION

Two forest soils of differing textures were selected for this study. The first soil had a sandy loam texture (78% sand, 18% silt, and 4% clay), was classified as an Inceptisol (USDA, 2006) with granitic parent material, and had an organic matter content of 6.8%. The second soil had a silt loam texture (58% sand, 40% silt, and 2% clay), was classi-

fied as an Andisol (USDA, 2006), consisted primarily of volcanic ash from the Mt. Mazama eruption 7700 years BP (Zdanowicz et al., 1999), and had an organic matter content of 7.9%. Both soils were collected from the top 20 cm of mineral soil in undisturbed forest areas in northern Idaho, and both represent two major soil orders for forested sites of this region. The soil was sieved (2 mm) before biochar was surface applied or mixed at equivalent rates of 0, 1, 5, and 10 Mg ha<sup>-1</sup>. All infiltration measurements (WDPT, MDI, and MED) were examined at five soil moisture contents: 0% (oven dry), 25%, 50%, 75%, and 100% of saturation. At 100% saturation, all air-filled pores were filled with water. Soil moisture contents were determined based on preliminary field capacity and permanent wilting point measurements of each soil type (Klute, 1986). Available water holding capacity (the difference between permanent wilting point and field capacity) for the Inceptisol was 32%, whereas the Andisol had a water holding capacity of 54%.

Unconsolidated soil was placed in a 20 × 30 × 2 cm pan and oven-dried for 24 h at 60°C after each moisture content test so that soil was re-wetted for each testing condition. After drying, water was added (by volume) and thoroughly mixed in to achieve the desired moisture content prior to biochar addition and infiltration testing. The soil equilibrated for 24 h after water was added and before infiltration testing. Biochar was air-dried and was then either surface applied or uniformly mixed into the mineral soil (fig. 1). Each undrained pan was divided into four equal parts to represent the replicates of each treatment. Based on the hydrophobicity work of Doerr (1998), we assumed that relatively homogeneous soil samples in a laboratory setting would be broadly representative of a field setting.



Figure 1. Tension infiltrometer on surface-applied biochar (5 Mg ha<sup>-1</sup> application rate) on granitic Inceptisol. Background pan is 10 Mg ha<sup>-1</sup> application rate.

## BIOCHAR PRODUCTION

Biochar was produced using a Biochar Engineering Corporation (BEC, Boulder, Colo.) mobile U5 Beta pyrolysis system equipped with a stack thermal oxidizer for emission control. The pyrolysis was a two-stage process involving feedstock having a short exposure to temperatures of 700°C to 750°C and then having a relatively longer exposure to a lower-temperature sweep gas. A limited amount of oxygen was available at the beginning of the process, rather than an exclusively anaerobic carbonization as is common in most biochar production. At the start of the process, material was loaded into a hopper, which fed a conveyor that metered material into the first reactor. The feedstock for biochar production was from mixed conifer (consisting of lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine) beetle salvage harvest residues. Although the biochar produced was in a range of particle sizes, this study used biochar with a particle size range of 0.5 to 2.0 mm. The bulk density of the biochar was 0.13 Mg m<sup>-3</sup>.

## WATER REPELLENCY TESTS

Four replicates of each water repellency test (MDI, WDPT, and MED) for each soil moisture content, and one of the two biochar treatments (surface applied or mixed) were completed. Each water repellency test started with oven-dry soil, which was brought to the appropriate percentage of soil saturation, and then biochar added so that each test (mixed or surface applied on each soil type) served as its own experiment. The 0% saturated (oven-dried) treatment with no biochar added for each soil type (Inceptisol and Andisol) served as the control. Care was taken to ensure that measurements from one test area did not influence the moisture content of the neighboring soil section.

The following water repellency tests were conducted on both soils at five levels of soil saturation, four biochar application rates, and with mixed or surface applied biochar:

### MDI

A Mini Disk Infiltrometer (model S, Decagon Devices, Inc., Pullman, Wash.) was used, and the volume of water that infiltrated in 1 min was recorded (Robichaud et al., 2008). One test was conducted in each of the four replicates (for each soil and biochar application method,  $n = \text{five moisture contents} \times \text{four biochar rates} \times \text{four replicates} = 80$  MDI measurements). The MDI device maintains a constant tension head of 5 mm and has a porous disk of 31 mm diameter (Lewis et al., 2006; Robichaud et al., 2008).

### WDPT

WDPT was conducted on eight evenly spaced points in each of the four replicates (for each soil and biochar application method,  $n = \text{five moisture contents} \times \text{four biochar rates} \times \text{four replicates} \times \text{eight points} = 640$  points). A distilled water drop (~20°C) was placed on the soil surface using an eyedropper (Doerr, 1998; Letey 2001), and the time required for complete infiltration of each drop was measured (or until 5 min had passed).

### MED

For the MED test, drops of increasing surface tensions (decreasing ethanol concentrations) were applied to the soil

surface until the drop resisted infiltration. The ethanol concentrations used in this study were 0%, 3%, 5%, 11%, 13%, 18%, 24%, and 36% (for each soil and biochar application method,  $n = \text{five moisture contents} \times \text{four biochar rates} \times \text{four replicates} = \sim 80$  MED measurements; the total number of drops was dependent on the level of water repellency). Drops (0.05 mL) of prepared solutions were applied to a smoothed soil surface using an eyedropper. Increasing concentrations were used until drop penetration occurred within 3 s (Doerr, 1998). The range of concentrations used for the MED test encompasses typical field water repellency conditions (Doerr, 1998). To facilitate MED statistical analyses, the MED values were categorized from 1 (very hydrophilic) to 7 (extremely hydrophobic) (Doerr, 1998), with 0% ethanol as very hydrophilic and 36% ethanol as extremely hydrophobic. For both the WDPT and MED tests, drops were placed on the soil surface from no higher than 5 mm to avoid excess kinetic energy that might disrupt the soil or biochar surface (Letey, 1969).

## STATISTICAL ANALYSES

We used the generalized linear mixed model in SAS (SAS, 1990). For direct comparison of treatment application rate within each soil moisture content and soil type, MDI, WDPT, and MED means were tested for significant differences against the control (no biochar, 0% moisture content) using Tukey's multiple comparison test. Each soil type (granitic or volcanic ash), water repellency test method, and biochar mixing method (surface applied or mixed) was analyzed separately (one soil type  $\times$  five soil moisture conditions  $\times$  four biochar rates  $\times$  four replicates). We chose to conduct separate analyses because our recommendations to land managers would likely be based on soil textural class and biochar application method. Statistical significance was assigned at the  $\alpha = 0.05$  level.

## RESULTS

### TENSION INFILTRMETER

Biochar application rate and method (surface or mixed application) and soil moisture content significantly affected water infiltration rate for both the sandy loam Inceptisol and the silt loam Andisol (table 1). At 0% soil saturation (oven dry) moisture content, the surface application of biochar on both the Inceptisol and Andisol significantly reduced infiltration with an application rate of 5 Mg ha<sup>-1</sup>. Mixing biochar into the mineral soil had no effect on infiltration until the application rate was 10 Mg ha<sup>-1</sup>. As soil moisture increased above 25% saturation, the infiltration rate with MDI decreased.

When the Inceptisol was relatively dry (0%, 25%, and 50% saturation), with 1 Mg ha<sup>-1</sup> biochar mixed into the mineral soil, it had nearly twice the infiltration rate of the Andisol (59 vs. 21 mL min<sup>-1</sup> at 0% saturation). At the 1 Mg ha<sup>-1</sup> application rate, either mixing or surface applied, and 0% saturation, both soil orders had infiltration rates that did not significantly affect MDI rates as compared to the control. The mixing treatment allowed greater levels of biochar to be applied without a significant decrease in infiltration,

**Table 1. Mean water infiltration rate (mL min<sup>-1</sup>) using the tension infiltrometer (n = 4) after surface or mixing application of biochar at various application rates (Mg ha<sup>-1</sup>) to an Inceptisol and Andisol at differing soil moisture contents.<sup>[a]</sup>**

Biochar Application Method	Application Rate (Mg ha <sup>-1</sup> )	Granitic Inceptisol Moisture					Ash Cap Andisol Moisture				
		0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
Surface	0	66.2 c	4.1 c	2.5 c	0.8 a	0.3 a	33.0 b	1.8 a	1.5 b	2.6 b	0.3 a
	1	59.0 bc	2.0 b	1.3 b	0 a	0 a	33.0 b	0.5 a	1.0 a	3.3 b	0.3 a
	5	17.0 b	0.5 a	1.0 a	0.5 a	0.1 a	1.0 a	0 a	0.5 a	0 a	0 a
	10	0 a	0.3 a	0.3 a	0 a	0 a	0.3 a	0 a	0 a	0 a	0 a
Mixing	0	58.3 B	5.2 C	2.3 A	1.2 A	0.4 A	31.6 B	1.7 AB	1.9 A	2.6 B	0.5 A
	1	59.0 B	3.3 BC	2.5 A	0.1 A	0.4 A	21.0 B	2.0 C	0 A	2.5 B	0 A
	5	60.0 B	1.3 AB	1.7 A	1.0 A	0.5 A	17.0 B	1.3 AB	0 A	0.2 A	0 A
	10	18.0 A	0.8 A	1.0 A	0.9 A	0 A	2.5 A	0.5 A	0 A	0.2 A	0 A

<sup>[a]</sup> Means within the same column (percent soil saturation) followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple comparison test. Surface application data (lowercase letters) are not compared to mixing data (uppercase letters) since recommendations for biochar application will be site specific. Soil moisture ranged from 0% (oven dry) to 100% (saturated).

particularly at low soil moisture.

There was no significant decrease in MDI in the Andisol for the 1 Mg ha<sup>-1</sup> application rate with either the surface applied (33 mL min<sup>-1</sup>) or mixing (21 mL min<sup>-1</sup>) application method at 0% saturation. Additionally, there was no significant infiltration difference at 0% saturation for the 5 Mg ha<sup>-1</sup> application rate with the mixing application method. However, once the soil pores became filled with water, the infiltration rate dropped rapidly.

### WATER DROP PENETRATION TEST

For the Inceptisol, the WDPT times for the surface treatment with the 1 and 5 Mg ha<sup>-1</sup> application rates on oven-dry soil were not significantly different from the control (0 s at 1 Mg ha<sup>-1</sup> and 0.9 s at 5 Mg ha<sup>-1</sup>; table 2). However, the mixing treatment at 0% saturation showed no significant differences for all application rates. Surface application of biochar resulted in significant increases in WDPT time at 5 Mg ha<sup>-1</sup> when the soil moisture exceeded 25% saturation. Mixing biochar into the soil at 100% saturation

resulted in a significantly less WDPT time than no biochar addition at the same moisture content.

At 0% saturation, the Andisol with surface application had significantly greater WDPT times than the control (table 2), whereas the mixing treatment at the 1 Mg ha<sup>-1</sup> application rate and 0% saturation was not significantly different from the control. Although the WDPT time for surface application at the 1 Mg ha<sup>-1</sup> application rate and 0% saturation was significantly greater than the control, the other moisture contents were not. Mixing biochar into the soil gave WDPT values that were not significantly different from the control at 0% saturation and the 1 Mg ha<sup>-1</sup> application rate, but all other WDPT tests were greater than the control.

### MOLARITY OF ETHANOL DROPLET TEST

In the MED tests on the Inceptisol, the surface treatment resulted in a significant increase in MED, primarily at the 10 Mg ha<sup>-1</sup> application rate, at all moisture contents except when the soil was 100% saturated (table 3). When the soil was saturated, all surface treatments at all application rates

**Table 2. Mean water infiltration time (s) for the water drop penetration test (n = 32) after surface or mixing application of biochar at various application rates (Mg ha<sup>-1</sup>) on an Inceptisol and Andisol at differing soil moisture contents.<sup>[a]</sup>**

Biochar Application Method	Application Rate (Mg ha <sup>-1</sup> )	Granitic Inceptisol Moisture Content					Ash Cap Andisol Moisture Content				
		0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
Surface	0	0 a	25 a	4 a	0 a	150 a	0 a	4 a	0 a	0 a	0 a
	1	0 a	36 a	14 a	3 a	165 a	34 b	25 a	0 a	0 a	0 a
	5	0.9 a	242 b	144 b	108 b	246 b	291 c	116 b	35 b	19 b	87 b
	10	235 b	239 b	231 c	185 c	256 c	300 c	156 b	146 c	189 c	179 c
Mixing	0	0 A	8 A	2 A	0 A	145 B	0 A	3 A	0 A	0 A	0 A
	1	0 A	31 A	1 A	0 A	60 A	14 A	249 B	149 B	158 B	140 B
	5	0 A	253 B	66 B	148 B	57 A	32 B	291 B	145 B	230 C	186 C
	10	0 A	300 C	61 B	105 B	110 B	32 B	295 B	242 C	300 C	279 C

<sup>[a]</sup> Means within the same column (percent soil saturation) followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple comparison test. Surface application data (lowercase letters) are not compared to mixing data (uppercase letters) since recommendations for biochar application will be site specific. Soil moisture ranged from 0% (oven dry) to 100% (saturated).

**Table 3. Mean molarity of ethanol droplet class (1 = hydrophilic through 7 = hydrophobic) (n = 32) after surface or mixing application of biochar at various application rates (Mg ha<sup>-1</sup>) on an Inceptisol and Andisol at differing soil moisture contents.<sup>[a]</sup>**

Biochar Application Method	Application Rate (Mg ha <sup>-1</sup> )	Granitic Inceptisol Moisture Content					Ash Cap Andisol Moisture Content				
		0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
Surface	0	1 a	4 a	1 a	1 a	3 a	1 a	4 a	2 a	2 a	1 a
	1	1 a	5 ab	1 a	2 a	5 b	3 b	2 a	1 a	1 a	1 a
	5	1 a	5 ab	1 a	1 a	5 b	4 bc	5 b	2 a	1 a	3 b
	10	5 b	6 b	3 b	6 b	6 b	5 c	5 b	4 b	4 b	6 c
Mixing	0	1 A	2 A	1 A	1 A	2 A	1 A	1 A	2 A	2 A	1 A
	1	1 A	6 AB	1 A	1 A	1 A	2 A	6 B	1 A	3 B	4 B
	5	1 A	7 B	1 A	1 A	1 A	3 B	6 B	2 A	5 B	5 B
	10	1 A	7 B	1 A	1 A	1 A	3 B	7 B	1 A	6 B	6 B

<sup>[a]</sup> Means within the same column (percent soil saturation) followed by the same letter are not significantly different at the 0.05 level by Tukey's multiple comparison test. Surface application data (lowercase letters) are not compared to mixing data (uppercase letters) since recommendations for biochar application will be site specific. Soil moisture ranged from 0% (oven dry) to 100% (saturated).

had significantly higher MED values. Mixing biochar into the soil had relatively little impact on the MED rates except for the 25% saturated soil, where MED increased significantly at the 5 Mg ha<sup>-1</sup> application rate.

On the Andisol soil, biochar surface application resulted in a significant increase in MED at 0% saturation (MED classes 3, 4, and 5 vs. class 1). However, at higher moisture contents with the surface application method, MED class was unaffected at the 1 Mg ha<sup>-1</sup> rate. In addition, the mixing treatment resulted in significantly increased MED values at the 0%, 25%, 75%, and 100% moisture contents at an application rate of 5 Mg ha<sup>-1</sup>. At the 10 Mg ha<sup>-1</sup> application rate with mixing, all MED values were significantly higher than the control for all moisture contents except 50% saturation.

## DISCUSSION

Biochar has been proposed as a soil amendment to create long-term C storage in the soil, while improving soil physical conditions or reducing environmental pollution (Ippolito et al., 2012). Since biochar is similar to black C in that it is a relatively porous medium, once water repellency is overcome it has the potential to retain a significant amount of water for plant uptake or soil storage (Novak et al., 2009; McElligott et al., 2011). In some cases, biochar has been shown to enhance soil permeability, but its effectiveness is related to soil clay content (Lehmann, 2007). In our study, a granitic loamy sand (Inceptisol) and a volcanic ash cap silt loam (Andisol) soil, each with only a small proportion of clays, had biochar applied either as a surface or mixing treatment under varying soil moisture conditions and application rates.

Infiltration into the Inceptisol, as measured by MDI, was generally unaffected when biochar was mixed into the mineral soil and at application rates up to 5 Mg ha<sup>-1</sup> for most soil moisture conditions (table 1). This is similar to the Andisol with up to 5 Mg ha<sup>-1</sup> application rate except, in addition to statistically significant reductions in infiltration at 25% saturation moisture, MDI measurements were also lower at 75% saturation. Small statistical differences in MDI (and the other tests) could be caused by uneven application of biochar and would likely be undetectable in a field study. Uneven distribution of biochar is likely the reason for the variability in infiltration rates at the same biochar application rate (table 1). Figure 1 illustrates the non-uniformity of application at 5 Mg ha<sup>-1</sup>, which was even more pronounced with the 1 Mg ha<sup>-1</sup> application. Each test condition was established on dried and re-wetted soil; therefore, biochar application likely produced variable surface test conditions.

Results of the MDI test with biochar mixed into the mineral soil indicate that the process of mixing has less impact on water repellency than surface application of biochar. Mixing biochar into the soil, particularly at low soil moisture contents, resulted in greater water infiltration than surface application of biochar for both soil types. In forested situations, water infiltration into the soil profile occurs readily (Luce, 1995; Robichaud, 2000). Infiltration rates are

determined by both gravimetric forces (primarily movement into macropores) and tension forces (primarily movement into micropores) (Beven and Germann, 1982; Ward and Dorsey, 1995). For example, the granitic Inceptisol has more macropores and therefore higher overall infiltration rates than the finer-texture Andisol (tables 1 and 2). In addition, when soil water content increases, the tension forces diminish as smaller pores are filled with water (tables 1 and 2). In our laboratory study, the soil was added to pans with an impermeable base. When the soil water content approached saturation, there was little space remaining within the shallow soil profiles to take in additional water. The MED tests were likely less affected by soil water content, but the MED rates are likely a result of the soil texture and biochar addition (table 3). On freely drained upland sites, saturated soil conditions are much less likely. However, if they occur, increased runoff (as suggested by tables 1 and 2) can be expected even though forest soils generally have high hydraulic conductivity (Luce, 1995). On sites where infiltration might be limited, mixing biochar into the soil surface will likely be more beneficial than surface application.

Using the soil water repellency classifications for WDPT (Doerr, 1998), the surface and mixing application methods both resulted in classifying the Inceptisol with moderate to severe water repellency at the 5 Mg ha<sup>-1</sup> application rate for moisture contents of >25% saturation (table 2). However, the Andisol with the mixing application method and 1 Mg ha<sup>-1</sup> application rate was classified with moderate to severe water repellency. Similarly, Doerr (1998) developed a water repellency classification for MED. This method classifies the Inceptisol as very hydrophilic (MED class 1) to hydrophilic (MED class 2) at biochar application rates up to 5 Mg ha<sup>-1</sup>. Using the MED test, the mixing application method showed generally no significant differences in biochar additions even at the 10 Mg ha<sup>-1</sup> application rate for all soil moisture contents except 25% saturation. However, for the Andisol, the MED test showed that surface application resulted in an immediate increase in water repellency (slightly to strongly hydrophobic; classes 3, 4, and 5) at 0% moisture content. Increased soil moisture contents of ≥25% saturation with surface application did not result in a change in hydrophobicity at the low application rate. As with the MDI and WDPT, the MED data showed that the granitic coarser-textured Inceptisol was less affected by biochar application rate, and that mixing biochar into the soil matrix generally resulted in less water repellency. Surface application of biochar at 1 Mg ha<sup>-1</sup> showed anomalous data across all moisture contents for the Andisol (table 1), where mean water infiltration rates were not well correlated. As the soil pores became saturated and water began to puddle on the soil surface during the tests, distinguishing the rate of WDPT and MED became much more difficult. Most field-based water repellency data are collected post-fire when the soil moisture content is low (generally less than 25%; Letey et al., 2000; Robichaud et al., 2008). The WDPT and MDI tests both measure how long hydrophobicity (water repellency) persists on the soil surface and the time required for infiltration (Doerr, 1998) and have been widely used in laboratory settings (Roberts and Carbon, 1971; Brock and DeBano, 1991; Dekker and Ritsema, 1994;

Robichaud et al., 2008). Conversely, the MED test measures the surface tension at the soil surface (i.e., how strongly a drop is repelled by soil; Doerr, 1998), and research has linked surface tension with the persistence time of hydrophobicity (WDPT; Crockford et al., 1991; Harper and Gilkes, 1994). This information illustrates that soil moisture content could be used to determine the best measurement techniques for water repellency.

In this study, we did not have a forest floor layer on top of the mineral soil. Application of biochar to forest sites could be accomplished on both highly disturbed soils (e.g., log landings, skid trails) and on areas that have very little soil disturbance and therefore an intact forest floor. In addition, the presence of a forest floor layer may aid in the retention of biochar during wind or water erosion events. However, on sites where a forest floor is present, mixing biochar into the mineral soil should be minimized so that nutrient cycling processes are not disrupted (Coleman et al., 2010).

Differences in biochar application method and rate highlight the important role of soil texture in altering water relationships in the field. An increase in infiltration rate in biochar-amended soils will likely have greater benefits on coarse-textured soils (Crockford et al., 1991; Asai et al., 2009), whereas soils with high silt or clay fractions are less likely to benefit from biochar applications (DeBano, 1981; Lehman and Joseph, 2009). For example, on a sandy soil, Abel et al. (2013) found that the addition of biochar had no measureable effect on the wettability of soil columns. However, although both natural black C (found after wildfire or prescribed burns) and biochar are highly porous, their initial water repellency must be overcome if they are to help adsorb and retain water (Tinker and Knight, 2000; Atkinson et al., 2010).

Currently, many forest stands in the western U.S. are overstocked with small-diameter tree stems, which slow the growth of individual trees (Oliver and Larson, 1990; Woolf, 2008). Pre-commercial thinning is frequently used to restore ecological function, but the removed biomass must be disposed of. Typically, the amount of forest residues remaining after pre-commercial thinning operations ranges from 5 to 20 Mg ha<sup>-1</sup> in the western U.S. (Buford and Neary, 2010), and this material is often burned on-site in piles, resulting in damage to the soil, loss of the energy stored in the biomass, and release of greenhouse gases (Oliver and Larson, 1990; Coleman et al., 2010). Stand thinning increases forest health, but these harvest activities must simultaneously maintain soil productivity (Zabowski et al., 2000; Gundale and DeLuca, 2006). Several areas in the western U.S. have access to fixed or mobile fast-pyrolysis units, which turn excess forest biomass into biochar. Adding biochar to forest sites at a rate equivalent to 1 Mg ha<sup>-1</sup> on fine-textured soil or up to 5 Mg ha<sup>-1</sup> on coarse-textured soil will not likely result in an increase in water repellency or a subsequent decrease in water infiltration rates, particularly if the biochar is mixed into the mineral soil. Although biochar mixing into the mineral soil is difficult on forest sites, opportunities exist for mixing biochar into highly disturbed areas such as decommissioned roads, skid trails, and log landings where vegetation and

roots have been removed. Various pyrolysis methods, ignition temperatures, and feedstock types will alter the properties of biochar. This should be considered before applying biochar to forest sites (Zabowski et al., 2000; Coleman et al., 2010; Kinney et al., 2012). In the western U.S., many ecosystems typically receive inputs of black C through wildfire, and biochar may provide a source of charcoal for improved soil conditions on sites where fire has been suppressed (Gundale and DeLuca, 2006). Biochar applied to some forest soils can improve soil moisture conditions for better forest ecosystem productivity. Ancillary benefits of biochar additions include carbon sequestration, increased nutrient retention, and decreased leaching (McElligott et al., 2011; Robertson et al., 2012). In addition, biochar added to a forest site will likely sequester C longer than forest residues (Coleman et al., 2010; Kinney et al., 2012). However, care must be taken to limit disturbance of the forest floor in order to maintain inherent hydrologic function and site productivity (Curran and Howes, 2011). As noted by Kinney et al. (2012), biochar created under different temperature regimes will create different levels of water repellency. Therefore, on sites that are fine-textured or prone to erosion, biochar created at temperatures ranging from 550°C to 650°C may be more appropriate for forest soil applications.

## CONCLUSION

Biochar may be a suitable amendment to forest soils, particularly on sites where the soil is relatively coarse textured or where the biochar can be mixed into the mineral soil. For example, during soil restoration activities where decompaction is necessary (e.g., skid trail remediation, road decommissioning), biochar can be mixed into the mineral soil at application rates of up to 5 Mg ha<sup>-1</sup> on coarse-textured soil. Higher amounts of biochar could be considered for soil restoration activities where deep mixing may be needed. In addition, surface-applied biochar will likely not impact infiltration rates on coarse or fine-textured soils at lower application rates of up to 1 Mg ha<sup>-1</sup>. Recommended levels of biochar addition are approximately equivalent to the amount of woody biomass C removed from forest sites during thinning operations, and biochar could be used to offset changes in soil quality related to C removal (DeLuca and Aplet 2008). Developing biochar application methods to match forest sites and creating biochar for specific purposes should be investigated.

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