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The effect of addition of a wettable biochar on soil water repellency

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Summary

The potential of biochar to ameliorate soil water repellency has not been widely studied. Previous studies have focused on the potential for biochar to induce or exacerbate existing water repellency rather than alleviate it. This study investigates the effect of adding wettable biochar to water repellent soil by comparing the water drop penetration times (WDPT) of control and biochar-amended soil.

The potential of wettable biochar to act as a physical amendment to water repellent soil was evaluated by mixing coarsely ground biochar (CGB, particle size range 250–2000 μm) or finely ground biochar (FGB, particle size range < 250 μm) with one strongly and one severely naturally water repellent soil in various quantities, and measuring the WDPT for each mixture. When biochar particles did not fall within the range of existing soil particle diameters, an initial increase in both mean WDPT (WDPT_M) and variation in WDPT was observed with small additions of biochar. These effects possibly resulted from increased surface roughness and inhibition of infiltration by suspension of drops above the average soil-air interface at a few hydrophobic points. Both CGB and FGB reduced soil water repellency, FGB more effectively than CGB. Adding 10% w/w FGB reduced soil WDPT by 50%, and 25% FGB eliminated repellency. Direct absorption of water by biochar and an increase in soil surface area in contact with water are likely the predominant physical mechanisms involved. This exploratory study suggests biochar has the potential to amend water repellent soil.

Introduction

The use of biochar as a soil amendment has become an important area of research. Until recently, interests have been mainly in the effects of biochar application on carbon sequestration and nutrient and water retention to improve agricultural soil (Sohi *et al.,* 2010). More recently, biochar production and application have been evaluated for the remediation of contaminated soil. A study by Debela *et al.* (2011) found that when biochar feedstock and contaminated soil were pyrolysed together, heavy metals could be encapsulated by the biochar during pyrolysis and rendered unavailable. Similarly, Beesley & Marmiroli (2011) found Cd and Zn levels decreased significantly when leachate from a contaminated soil was filtered through biochar columns.

Soil water repellency (SWR) can have natural or anthropogenic causes. Plant decomposition can release long-chain fatty acids, alkanes and lipids, which coat soil particles, decrease the surface tension and restrict water infiltration at the soil surface (Morley *et al.*, 2005; Koch & Ensikat, 2008). Water repellency can also develop after an oil spill, as hydrocarbons enter pore spaces and decrease the soil surface tension (Roy & McGill, 2003). SWR occurs in many parts of the world regardless of climate or soil texture. In Australia, for example, SWR frequently develops under eucalypt stands and following wildfires. Wildfires mainly enhance existing water repellency rather than introduce it, and the degree of repellency observed depends on the severity of the fire, the vegetation community present and soil type (Doerr *et al.*, 2009; DeBano, 2000).

The reduced wettability of water repellent soil areas not only enhances the risk of overland flow and associated erosion, but it can also reduce vegetation recovery and prolong the time burned areas are susceptible to erosion (DeBano, 2000). Mitigation measures to encourage faster revegetation and decrease erodibility vary depending on the cause and the characteristics of the affected site. In some areas, surfactants are used to increase soil surface tension and allow water infiltration (Barton & Colmer, 2011), whereas in others mechanical disturbance or tillage are used to disperse hydrophobic soil among more wettable soil, exposing soil to air for organic compounds to mineralize (Blanco-Canqui, 2011; Harper *et al.*, 2000). Direct addition of a wettable material to the soil has also been successful, such as the addition of clay to Australian agricultural. Harper & Gilkes (1994) found SWR was reduced with a 1% increase in clay content, and eliminated with a 5% increase. Kaolin clays have been found to be most effective in rendering soils wettable (McKissock *et al*., 1999; Lichner *et al*., 2006).

Biochar, like clay, can have very large surface areas and is strongly adsorbent. Therefore, biochar could potentially amend water repellent soil in a similar way to clay. A report by the European Commission (Verheijen *et al.*, 2009) identified a research gap on the effect of biochar on water repellent soil, and several studies since have included the effects of water repellency in their research on biochar. Abel *et al.* (2013) investigated the effect of biochar (produced from maize feedstock and pyrolysed at 750°C) on soil water retention and repellency through laboratory and field trials of soil columns mixed with 0, 1, 2.5 or 5% w/w biochar. The five soils they used were all sands or loamy sands taken from the top layer of a Regosol, a Luvisol or a former sewage farm site. Their organic matter contents ranged from 0.1 to 9.1%, and they were wettable before biochar application. At the end of the six–month trial, Abel *et al.* (2013) concluded that biochar had no effect on soil water repellency, as water drop penetration time (WDPT) tests revealed no increase in the time to infiltration.

Herath *et al.* (2013) tested whether biochar could improve soil water-holding capacity and drainage capabilities by studying the effect of two biochars on the bulk density, aggregate stability, saturated hydraulic conductivity, volumetric water content and water repellency of two silt loams from permanent pastures. One soil was slightly repellent (WDPT 5–60 seconds) with 41.7 g C kg^{-1} soil and the other was strongly repellent (WDPT 1–60 minutes) with 102 g C kg^{-1} soil. The biochars were produced from corn stover feedstock and were pyrolysed at 350°C and 550°C. They were applied to each soil at a rate of 7.18 t C ha^{-1} and packed into columns where they were maintained at field capacity for 295 days. In terms of water repellency alone, at the end of the ~300-day study, the strongly repellent soil had become slightly repellent and the slightly repellent soil remained the same. This led to the conclusion that biochar had no significant effect on water repellency.

The properties of biochar depend largely on their feedstock (i.e. type of biomass used) and pyrolysis conditions. Biochar produced at temperatures < 500°C retains many organic functional groups from the original feedstock, and is therefore usually water repellent (Kinney *et al.*, 2012; Antal & Grønli, 2003). Pyrolysis temperatures > 500°C will volatilize the organic groups linked to hydrophobicity, rendering the biochar hydrophilic. Kinney *et al.* (2012) found that biochars from three different feedstocks followed the same trend: pyrolysis at 300°C produced extremely hydrophobic biochar, but hydrophobicity decreased with increasing temperature and at temperatures > 500°C the biochar produced was wettable.

To evaluate the potential of biochar as a physical amendment for water repellent soil, three questions were posed.

1) Does the addition of a wettable biochar have a significant effect on the water drop penetration time (WDPT) when mixed into a water repellent soil?
2) How does the addition of biochar affect soil WDPT compared to the addition of wettable soil?
3) If wettable biochar does reduce soil water repellency, is there an optimal application rate?

A laboratory experiment was designed to explore the effects of various quantities of biochar on two water repellent soils. Wettable coarsely or finely ground biochars were mixed with strongly repellent coarse sand (CS) and extremely repellent medium sand (MS) in w/w proportions of 5, 10, 25 and 40%. These ratios were chosen to gain a fundamental understanding of the effect biochar might have rather than to mimic the rates of field applications. Mixtures of wettable and water repellent soil were created as controls, and the water repellency of each mixture was tested with the WDPT test. The effect of biochar addition on mean soil WDPT (WDPT_M) was then compared to that of wettable soil.

Materials and methods

Naturally water repellent soil

Two naturally water repellent soils were studied: CS, a coarse, relatively homogenous sand with low organic carbon content (Arenosol; IUSS Working Group WRB, 2006), taken beneath grass cover from dunes in Nicholaston, Gower, Wales; and MS, a medium sand with a similar mean texture to CS but more organic carbon (Anthrosol; IUSS Working Group WRB, 2006), taken from a Leyland Cypress stand (*Cuprocyparis leylandii* (A.B. Jacks. & Dallim.) on the Singleton Campus in Swansea, Wales (Table 1). Previous studies classified both soils as highly repellent (CS is the 'Nicholaston sand' characterised in Doerr *et al.* (2005); and MS is the 'University sand' characterised by Hallin *et al.* (2013)).

Both soil samples were taken from the upper 5 cm of the soil profile, and any litter layer was removed beforehand. The soil was air-dried at approximately 20°C and then sieved to 2 mm to remove large fragments of organic matter.

Preparation of wettable analogues

Mixtures of wettable and water repellent soil were created as controls to determine whether any effects observed in biochar:soil mixtures were due to the addition of a wettable fraction to a water repellent system, or to biochar-specific properties. Rather than introduce new soils, wettable analogues were prepared by stripping organic matter from CS and MS. A sample of soil was washed with 0.1 M NaOH for 30 minutes to remove organic matter and then rinsed with distilled water until the solution reached a neutral pH. The washed soil was oven-dried at 105°C for 24 to 48 hours, then allowed to cool to 20°C. This process was repeated until water drops applied to a small subsample infiltrated consistently within 5 s. The wettable soil analogues obtained from CS and MS are identified as CS_w and MS_w, respectively. Their mean particle diameter, range of particle diameter and total organic carbon content are given in Table 1.

Biochar

Biochar was provided by the UK Biochar Research Centre in Edinburgh. This was prepared from a mixed softwood feedstock of pine and spruce pellets (Puffin Pellets, Banff, Scotland), pyrolysed in a 250-mm diameter rotary kiln at a peak temperature of 700°C with intermediate mean residence time. Coarsely ground biochar (CGB, particle-size range 250 to 2000 μm) and finely ground biochar (FGB, particle-size range < 250 μm) were prepared by grinding these pellets with a pestle and mortar followed by sieving through a 250 μm sieve.

Particle-size distributions for soil and course and fine biochars

Soil particle size was measured by laser diffraction with a Malvern (Malvern, UK) Mastersizer 2000. Three subsamples of each water repellent soil and its analogue were analysed for particle size (μm) by volume (%). Particle-size distributions (PSD) for CS and MS are given in Figure 1a.

A Beckman Coulter (Brea, USA) LS 230 Dry Powder Module (Model Number DPM) was used to measure the PSD for CGB and FGB (Figure 1b), and summary statistics are given in Table 2.

Particle-size distribution for biochar:soil mixtures

Weighted volume fractions were used to calculate the PSD for each component according to Equation (1).

$$V_{\mathrm{T_i}} = \frac{(V_{\mathrm{B_i}} \times V_{\mathrm{B_T}}) + (V_{\mathrm{S_i}} + V_{\mathrm{S_T}})}{(V_{\mathrm{B_T}} + V_{\mathrm{S_T}})} \times 100, \tag{1}$$

where $V_{\mathrm{T_i}}$ is the total volume (%) of particles in the mixture at any given diameter ‘i’, $V_{\mathrm{B_i}}$ and $V_{\mathrm{S_i}}$ are the volume fractions of biochar and soil at diameter ‘i’, and $V_{\mathrm{B_T}}$ and $V_{\mathrm{S_T}}$ are the total volumes of biochar and soil in the mixture, respectively.

Total volumes of biochar and soil for each 200 g mixture were calculated with Equations (2) and (3), respectively, where M is the mass fraction of biochar or soil in the mixture (e.g. 0.05 biochar and 0.95 soil), 200 refers to the mass of the mixture and ρ is the mean density of each material (g cm^{-3}).

$$V_{\mathrm{B_T}} = (M_{\mathrm{B}} \times 200)/\rho_{\mathrm{B}} \tag{2}$$

$$V_{\mathrm{S_T}} = (M_{\mathrm{S}} \times 200)/\rho_{\mathrm{S}} \tag{3}$$

Densities were measured by packing each solid loosely into a 10 cm^3 volumetric flask, tapping to settle until the meniscus mark was reached. Flasks were then weighed, and the entire process was repeated until the difference between two replicates was < 5% of the sample mass. This gave: $\rho_{\mathrm{CS}} = 1.56 \pm 0.01$; $\rho_{\mathrm{MS}} = 0.930 \pm 0.080$; $\rho_{\mathrm{CGB}} = 0.388 \pm 0.004$; and $\rho_{\mathrm{FGB}} = 0.645 \pm 0.003$.

Preparation of biochar:soil mixtures and WDPT tests

Soil samples were coned and quartered (Jackson, 1958) to ensure homogeneity when obtaining the desired weight for each mixture. Soil and biochar fractions were weighed to ± 0.0001 g, and all materials were then kept in a constant temperature and humidity room for 24 hours prior to and following mixing at 18 ± 0.5°C and 29 ± 3% relative humidity (RH). To avoid uneven settling, soil and biochar were kept separate until they were mixed in a 22.5 × 31.5-cm tray. First the soil was spread evenly across the tray, then biochar was spread evenly across the soil surface. The two were incorporated manually until no distinct patches of biochar or soil were evident and the surface of the mixture appeared homogenous.

Previous research by Hallin *et al.* (2013) investigated the effect of drop volume in WDPT classification, and found that in general, larger drops (80, 200 μl) provide more of an average water repellency class for the soil, whereas smaller drops (15, 20 μl) better reflect surface heterogeneities. Both 20 and 200 μl drops were used in this study to obtain information on both surface heterogeneities and overall average water repellency of the biochar:soil mixtures. Drops of distilled water (20 and 200 μl), equilibrated to 18 ± 0.5°C, were applied from ≤ 1 cm height to each tray of soil following a grid pattern with a spacing of 3 × 2 cm . In total, 104 drops of each volume were applied to each tray with an Eppendorf (Hamburg, Germany) Repeater Plus pipette. The time from placement to complete infiltration was recorded for each drop as the WDPT.

Descriptive statistics and statistical analyses for WDPT measurements

Descriptive statistics (mean, standard deviation and variance) were calculated with the equations for normal distributions. Error estimates are quoted as ± 1 standard deviation from the mean, except when only one sample was available, in which case only the sample value is reported.

Any irregular drops, such as those that were dispensed unevenly or those that rolled across the surface, were removed from the data sets before statistical analysis of WDPT results. The results from a one-way analysis of variance (ANOVA) indicated that there were significant differences between group means for all comparisons ($P < 0.05$). Therefore, two-tailed *t*-tests ($\alpha = 0.05$) were applied to explore the data further. Comparisons were made between results from the same mixture and between results from different mixtures made with the same grade of biochar.

Percentage change in water repellency (ΔWDPT) was calculated for each mixture according to Equation (4), where T_{S} is $\mathrm{WDPT_M}$ for soil and T_{M} is $\mathrm{WDPT_M}$ for the biochar:soil mixture.

$$\left(\frac{T_S - T_M}{T_S}\right) \times 100\% = \Delta WDPT \qquad (4)$$

Microscope photographs of hydrophobized AWS:biochar mixtures

Acid-washed sand (AWS), hydrophobized with octadecanoic acid according to the method described in Hallin (2013) and Mainwaring *et al.* (2013), was mixed with FGB to create a model system for the biochar:soil mixtures that would photograph well under the microscope.

Photographs were taken with Fuji (Tokyo, Japan) Reala colour film (ASA 100) with an Olympus (Shinjuku, Japan) BH2 microscope fitted with a DPlan 4PO 4× objective lens and an NFK 3.3× LD camera lens with an Olympus OM 4 camera. Samples were illuminated from the side with a Schott (Mainz, Germany) KL1500 fibre optic light through a Wratten (New York, USA) 80B filter.

Preliminary studies

For biochar to be considered a potential SWR amendment, the practicalities involved in its application must be considered in conjunction with its efficacy. Therefore, the wettability of different grades of biochar (pellets, CGB, FGB) and the suitability of different application techniques were evaluated before preparation of biochar:soil mixtures. Biochar wettability was evaluated by applying water drops directly to the surface of biochar pellets and dishes of CGB and FGB. All drops infiltrated immediately on contact (WDPT < 1 s).

Mixtures of w/w 10% biochar and 90% CS (10:90) were prepared with each grade of biochar to evaluate the application of biochar to the surface versus thorough mixing of biochar into the soil.

Pellets were immediately ruled out for further study because their size prevented them being mixed effectively with the soil. When applied to the surface, they created a distinct layer on top of the soil and water infiltrated the pellet before touching the soil. Both CGB and FGB could be mixed into the soil or applied to the surface, and both grades reduced WDPT when tested with nine 20 and 200 μl drops. Surface-applied biochar resulted in uneven wetting and surface puddles, therefore the final biochar:soil mixtures were created by thoroughly mixing CGB or FGB throughout the soil.

Previous work by Hallin *et al.* (2013) tested mixtures of 90, 75 and 50% water repellent soil with 10, 25 and 50% w/w wettable analogue soil. The same ratios were used for biochar:soil mixtures to enable direct comparisons to wettable soil. The 50:50 biochar:soil mixtures were unsuccessful, however, as the biochar settled into a separate layer from the soil even after mixing. A trial 40:60 biochar:soil mixture did not separate, and replaced the 50:50 mixtures. An additional mixture, 5:95 biochar:soil, was also included to evaluate the effects of smaller quantities of biochar on SWR.

Results

Particle-size distributions of biochar:soil and soil:soil mixtures

Addition of either CGB or FGB to CS introduces a new, wide range of particle sizes to the soil, but for MS the effect of mixing on PSD is negligible (Figure 1).

The mean particle diameters of CS_W and MS_W are not much different from those of CS and MS, but the loss of organic matter and very small clay particles through the rinsing process results in a narrower PSD, especially for MS_W (Figure 2). For CS, which had little organic matter or small clay particles, the effect is negligible, but for MS this narrows the particle-size distribution in the mixture.

Effect of drop volume on WDPT

The WDPT results for biochar:soil mixtures are given in Figures 3 and 4. General trends for 200 µl indicate that $WDPT_M$ decreases with increasing biochar addition (Figure 3). This trend is also observed in the results from 20 µl drops, but not to the same extent (Figure 4). In accordance with Hallin *et al.* (2013), 20 µl drops show more variation in WDPT than 200 µl drops, likely because the smaller footprint of a 20 µl drop encounters greater surface heterogeneity than the larger footprint of the 200 µl drop. The smaller drops reflect the greater degree of heterogeneity within the 5 and 10% biochar mixtures, especially those with CGB, and as a result $WDPT_M$ shows no trend. The variation in the results is large for most mixtures with ≥ 25% biochar;, the trend with 200 µl drops becomes evident at this point, as $WDPT_M$ is lowest for all mixes with 40% biochar.

The results of ANOVA are given in Table 3. Two-tailed *t*-tests indicate that the difference between 5 and 10% FGB mixtures is consistently significant, with 10% FGB resulting in smaller $WDPT_M$ values than 5% FGB. In contrast, the difference between 5 and 10% CGB is generally not statistically significant, with the exception of CGB:CS measured with 200 µl drops. There is no statistically significant difference between 25:75 and 40:60 mixes for either of the biochar:soil combinations or drop volumes; both mixtures have the smallest $\mathrm{WDPT_M}$ values.

Effectiveness of biochar versus wettable soil analogue in reducing SWR

Figure 5 shows the percentage reduction in $\mathrm{WDPT_M}$ with the addition of biochar or wettable soil analogue for all mixtures.

FGB is the more effective of the two biochars; it reduces soil water repellency by ≥ 60% in 10:90 mixtures compared to an approximate 30% reduction with CGB. FGB is also equally effective in both soils: ≥ 25% FGB added to either soil eliminates SWR, whereas ≥ 25% CGB is more effective in CS.

On a % w/w basis, FGB is also more effective at reducing water repellency than the wettable soil analogues when tested with 200 µl drops (Figure 5a). The FGB:CS mixtures are at least 25% less repellent than the corresponding $\mathrm{CS_W}$:CS mixtures, and 25% FGB removes repellency in both soils, whereas the mixtures with 50% wettable analogue still show signs of water repellency. Once again CGB is not consistently effective, and results vary between the two soils. Reductions in water repellency are consistently greater for $\mathrm{CS_W}$ mixes than for CGB mixes, sometimes by 30% or more. However, CGB is effective in the medium sand: 40% CGB reduces water repellency by approximately 96% compared to the 90% reduction achieved with 50% $\mathrm{MS_W}$.

When tested with 20 µl drops (Figure 5b), the wettable soil analogues appear to be more effective than additions of either CGB or FGB; 10% $\mathrm{CS_W}$ reduces water repellency in CS by approximately 90%, compared to a 75% reduction by 10% FGB. Furthermore, 200 µl drops show no repellency with > 25% biochar present, whereas 20 µl drops show some repellency even with 40% CGB, but none with ≥ 25% wettable soil analogue.

Discussion

The following discussion focuses on results from 200 µl drops, which best reflect the average degree of water repellency.

Effect of particle-size distribution on WDPT

Increased variation in $WDPT_M$ is observed in results from both CGB and FGB for 5:95 biochar:CS mixtures (Figure 3), but not for biochar:MS mixtures, suggesting a soil-specific change was introduced by biochar. This variation might arise from increased surface roughness: the addition of CGB and FGB to CS introduced a new range of fine particle sizes to the coarse sand, which changed the topography of the surface by increasing surface roughness. The changes to surface topography and roughness in CS through biochar addition might inhibit infiltration by the suspension of drops above the position of the average soil-air interface at a few hydrophobic points. Soil particles of comparable size to those of biochar in CGB and FGB are already present in MS, so the addition of biochar to MS does not affect surface topography in the same way as for CS (Figure 1).

Additional biochar would increase surface roughness further, but would also be likely to increase the probability of contact between the water drop and biochar. Photomicrographs of hydrophobized AWS mixed with biochar show that biochar adheres to AWS particles (Figure 6), suggesting that it could cover the hydrophobic compounds adsorbed to a soil particle and provide a wettable surface. The controlling factor for water infiltration then becomes wettability of the biochar rather than surface roughness, similar to the mechanism proposed for clay amendment (Müller & Deurer, 2011).

The chemical effect of biochar on soil may also be important (Hallin, 2013), but biochar in contact with a water drop can physically decrease $\mathrm{WDPT_M}$ in several ways. The high porosity and wettability of CGB or FGB allows it to act like a sponge and soak up water rapidly. This is unlikely to make a noticeable difference at 5% levels because there is little biochar at the surface. Figure 7 shows theoretical contact areas between water drops and CGB:soil mixtures, and illustrates that drops are unlikely to come into contact with much biochar for 5:95 mixtures. If water drop-biochar contact were made, the wettable biochar would absorb water from the drop like a sponge.

The wettability and porosity of biochar pellets was estimated by assessing their average water uptake. Based on the mass difference between dry and saturated biochar and the volume of water absorbed, pellet porosity was estimated to be approximately 55%. Even assuming that porosity remained at ~ 55% after grinding, the largest FGB particle would still be able to absorb only about 0.05% of a 200 μl drop. Similarly, the largest CGB particle could absorb ~ 1.5% of a 200 μl drop. The 'sponge effect' is, therefore, more likely to make a noticeable difference when enough biochar is present so that its particles are in contact with each other and can form preferential flow paths through the soil (Figure 7, 40:60 mixtures).

A rough, but useful, estimate of potential soil particle cover by biochar can be calculated from the ratio of mean particle diameters and the proportions of each component within the mixture if we make the following assumptions: (i) a biochar particle will bind to a soil particle only along one side, and (ii) soil particles are roughly spherical and biochar particles are roughly cuboid. Results of these calculations for soil particle cover by biochar are given in Table 4; even for the largest mixture ratio CGB could cover only a very small fraction of the soil particle area, whereas FGB could potentially cover a considerable fraction of both CS and MS particles.

Biochar might also reduce $WDPT_M$ by increasing the effective surface area of soil in contact with water. A water drop in contact with a water repellent soil surface will be attracted to the polar functional groups present in the hydrophobic compounds coating the soil (Bachmann & van der Ploeg, 2002; Roy & McGill, 2002). As water adsorbs to the more wettable parts of the soil particle surfaces, the surface energy of the soil-water interface decreases and the initial soil-water contact angle decreases, eventually decreasing sufficiently for the drop to overcome repellency and spread across the soil surface. According to Leelamanie & Karube (2009), this process is repeated on contact with each subsequent layer of soil until the drop has infiltrated completely; the total time required is the WDPT. When biochar absorbs water from the drop or the surrounding soil, it increases the total area of soil exposed to water. Absorbed water would come into contact with subsurface soil through biochar surfaces, and contribute to the overall wetting process and reduction in $WDPT_M$.

Potential for biochar as a soil amendment

Before any recommendations can be made on the potential of biochar as a SWR amendment, laboratory and field trials with soil of different textures and different degrees of water repellency are required. A range of water contents relevant to specific applications should be considered. For example, irrigated soil often shows water repellency most strongly when almost air dry, so further testing of biochar:soil mixtures at water contents equivalent to air-dry conditions should be done before any application to irrigated soil. Additionally, its longer-term efficacy needs to be evaluated and biochar needs to be compared to other amendments to determine its relative effectiveness both physically and economically.

While bearing these caveats in mind, these analyses indicate that both FGB and CGB could potentially be suitable amendments for water repellent soil. Biochar was generally more effective at reducing water repellency than the wettable soil analogues, which suggests that biochar has an effect in soil beyond that of simply adding a wettable component to a water repellent system. The effectiveness of biochar, however, varied considerably with soil texture and biochar particle size. FGB additions ≥ 25% eliminated water repellency in both medium and sandy soil, and FGB often reduced water repellency more than CGB, which suggests that a finely ground biochar might be more effective than coarse biochar.

The most comparable soil amendment to FGB currently in use is probably clay (Cann 2000; Dlapa *et al.,* 2004). Both wettable biochar and clay have similar physical effects on soil, i.e. they increase the hydrophilic surface area for water infiltration within the soil (Cann, 2000; Lichner *et al.* 2006), but biochar has the added benefit of being a carbon source and of storing nutrients for slow release over time, as well as being a possible route for carbon capture of atmospheric CO_2. Biochar is not inert, however, and it will eventually decompose, which might affect its ability to act as a long-term remediation strategy for water repellent soil. Residence times of biochar in soil will vary, but Woolf & Lehmann (2012) estimate a mean half-life of 1000 years for the recalcitrant portion. Clay amendments are similarly time-dependent; clay will not degrade like biochar, but natural soil development processes over similar time scales (~1000 years) can translocate clay deeper in the soil profile. Over shorter time scales clay has been shown to be effective: Van Dam *et al.* (1990) found that clay was still present in clay-amended topsoil 30 years after application, and Ward & Oades (1993) reported anecdotal evidence that claims clay was effective in reducing SWR for at least 20 years after application. The lifetime of biochar within the soil and its long-term effectiveness within water repellent soil as they weather and change is another area that must be explored.

Rates of biochar application must also be considered. For example, golf courses in the USA, which are frequently affected by SWR (Kostka, 2000), stipulate a clay content of no more than 3% for the root zone soil (USGA, 1973). Similar limits would probably be applied here to biochar to preserve the textural integrity and playability of greens, making large application rates, such as 25% FGB, unrealistic.

Like any amendment, the viability of applying biochar to reduce water repellency depends on its direct cost, the availability of cheaper alternatives, transport costs and on return for the investment. These factors vary considerably between potential applications, and an in-depth analysis is beyond the scope of this study. Biochar might be a feasible option for medium textured soil, such as the medium sand in this research, in areas where clay is not readily available but pyrolysis facilities can be built, or where less biochar is needed to reduce repellency, for example, localized problems with water repellency in high value areas such as in manicured landscapes and gardens. The environmental, social and potentially economic (through, for example, 'carbon credits') value of using biochar, might also become important considerations depending on the targeted application.

There are many unknowns about the effectiveness of biochar, including (but not limited to) the long-term effects of biochar addition on SWR and the effects of repeated wetting and drying cycles and of water repellency-inducing bacteria and fungi on biochar porosity and sorption capabilities. The results of this preliminary study, however, demonstrate that biochar has the potential to be used for this purpose.

Conclusions

Wettable biochar substantially increased the wettability of highly water repellent coarse- and medium-textured soil, more so than was achieved by adding wettable soil analogues. Of the three amendments tested (FGB, CGB and wettable soil analogue), FGB was most effective: 10% FGB reduced $WDPT_M$ more than larger quantities of CGB or wettable soil analogue. The addition of 10% FGB reduced water repellency by 50%, and 25% FGB eliminated water repellency in both the medium and coarse textured soils tested. The predominant physical mechanisms likely to be involved are: direct absorption of water by biochar; a decreased, or more rapidly decreasing, soil-water interfacial energy; and an increased surface area of soil in contact with water. When biochar particles did not fall within the range of existing soil particle diameters, an initial increase in $WDPT_M$ and variation in WDPT was observed, which might be explained by increased surface roughness and the resulting inhibition of infiltration by the suspension of drop above the position of the average soil-air interface at a few hydrophobic points.

The results presented and discussed here suggest that biochar has the potential to act as an amendment for water repellent soil, however, further laboratory and field trials are necessary.

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Table 1. Source locations and characteristics for naturally water repellent soil used in this study.

Sample Code	Coarse Sand (CS)	Medium Sand (MS)
Source location	Nicholaston, Wales, UK	Swansea University Campus, Wales, UK
Latitude and longitude	51°34'21"N; 4°08'2"W	51°36'34"N; 3°58'50"W
Textural class	Coarse sand	Medium sand
FAO classification	Arenosol	Anthrosol
Mean particle diameter/ mm	0.30 0.31[1]	0.41 0.28[2]
Particle diameter range/ mm	0.21 to 0.42 0.22 to 0.42[1]	0.08 to 1.18 0.13 to 0.60[2]
Total organic carbon/ %	0.57 ± 0.05 0.15 ± 0.01[1]	17.25 ± 0.76 1.33 ± 0.22[2]

[1] Wettable coarse sand analogue ($\mathrm{CS_W}$)

[2] Wettable medium sand analogue ($\mathrm{MS_W}$)

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Table 2. Summary statistics for coarsely ground (CGB) and finely ground (FGB) biochar particle size analyses. Note that distribution width (standard deviation/mean) is unitless.

		Median/ mm	Mean/ mm	Standard deviation/ mm	Distribution width
CGB*	Arithmetic	0.75	0.79	0.63	0.80
	Geometric		0.69	0.02	0.03
FGB†	Arithmetic	0.17	0.19	0.28	1.43
	Geometric		0.13	0.01	0.07

Particle size obtained with a Beckman Coulter LS 230 Dry Powder Module with settings as follows.
*auger, 71; vibration, 16; mean obscuration, 4 to 7%; chute tilt, slightly off maximum; hopper, full.
†auger, 21; vibration, 25 to 30; mean obscuration, 5 to 10%; chute tilt, full angle; hopper, 0.5 to 0.75 full.

Table 3. The results of ANOVA for coarsely ground (CGB) and finely ground (FGB) biochar mixtures with medium (MS) and coarse (CS) sand. Each listing under ‘Group Compared’ refers to all mixtures within that group (for example, CGB:MS 200 µl refers to an ANOVA in which the 5:95, 10:90, 25:75, and 40:60 mixes of CGB:MS, tested with 200 µl drops, are compared). Degrees of freedom (df) and the relevant *F* statistics are provided.

Groups Compared	$\mathrm{df}_{\mathrm{within}}$	$\mathrm{df}_{\mathrm{between}}$	F_{critical}	$F_{\mathrm{statistic}}$	P-value
CGB:MS 200 µl	366	3	2.63	541.4	3.62×10^{-134}
FGB:MS 200 µl	400	3	2.63	2548.6	3.09×10^{-260}
CGB:CS 200 µl	403	3	2.63	41.9	1.43×10^{-23}
FGB:CS 200 µl	391	3	2.63	90.7	1.41×10^{-44}
CGB:MS 20 µl	412	3	2.63	171.8	3.17×10^{-72}
FGB:MS 20 µl	410	3	2.63	257.5	6.67×10^{-94}
CGB:CS 20 µl	412	3	2.63	105.1	1.57×10^{-50}
FGB:CS 20 µl	408	3	2.63	188.6	1.01×10^{-76}

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Table 4. Ratio of coarsely ground (CGB) and finely ground (FGB) biochar to medium (MS) coarse (CS) sand soil surface areas, as calculated from the mean particle sizes.

	Ratio of biochar to soil surface area			
Mixture	CGB:CS	CGB:MS	FGB:CS	FGB:MS
5:95	0.0003	0.0001	0.87	0.31
10:90	0.0006	0.0002	1.83	0.65
25:75	0.0017	0.0006	5.50	1.96
40:60	0.0034	0.0012	11.0	3.92

Figure captions

Figure 1 Particle-size distributions for: (a) coarse sand (CS) and medium sand (MS), and (b) coarsely ground biochar (CGB) and finely ground biochar (FGB). Note the horizontal axis is a logarithmic scale.

Figure 2 Particle-size distributions for coarse sand (CS), medium sand (MS) and 50:50 mixtures of wettable coarse sand (CS_W) with CS, and wettable medium sand (MS_W) with MS. Note the horizontal axis is a logarithmic scale.

Figure 3 Water drop penetration time (WDPT) test results for 200 µl drops on coarsely ground (CGB) and finely ground (FGB) biochar mixtures with (a) medium sand (MS), and (b) coarse sand (CS).

Figure 4 Water drop penetration time (WDPT) test results for 20 µl drops on coarsely ground (CGB) and finely ground (FGB) biochar mixtures with (a) medium sand (MS), and (b) coarse sand (CS).

Figure 5 Percentage decrease in water repellency (ΔWDPT) of coarse sand (CS) and medium sand (MS) with increasing quantities of wettable coarse sand (CS_W), wettable medium sand (MS_W), coarsely ground biochar (CGB) or finely ground biochar (FGB) as measured by: (a) 200 µl, and (b) 20 µl drops.

Figure 6 Microphotographs of hydrophobized acid-washed sand mixed with: (a) 1% finely ground biochar (FGB) and (b) 10% FGB.

Figure 7 Model view of: (a) 200 µl and (b) 20 µl drops applied to the surface of coarsely ground biochar (CGB) mixtures with coarse sand (CS) and medium sand (MS) (SpherePack 1D (Farr, 2011)). In the packing arrangements spheres represent soil particles and cubes represent biochar. For both soil and biochar the particle-size distributions used are those obtained experimentally.

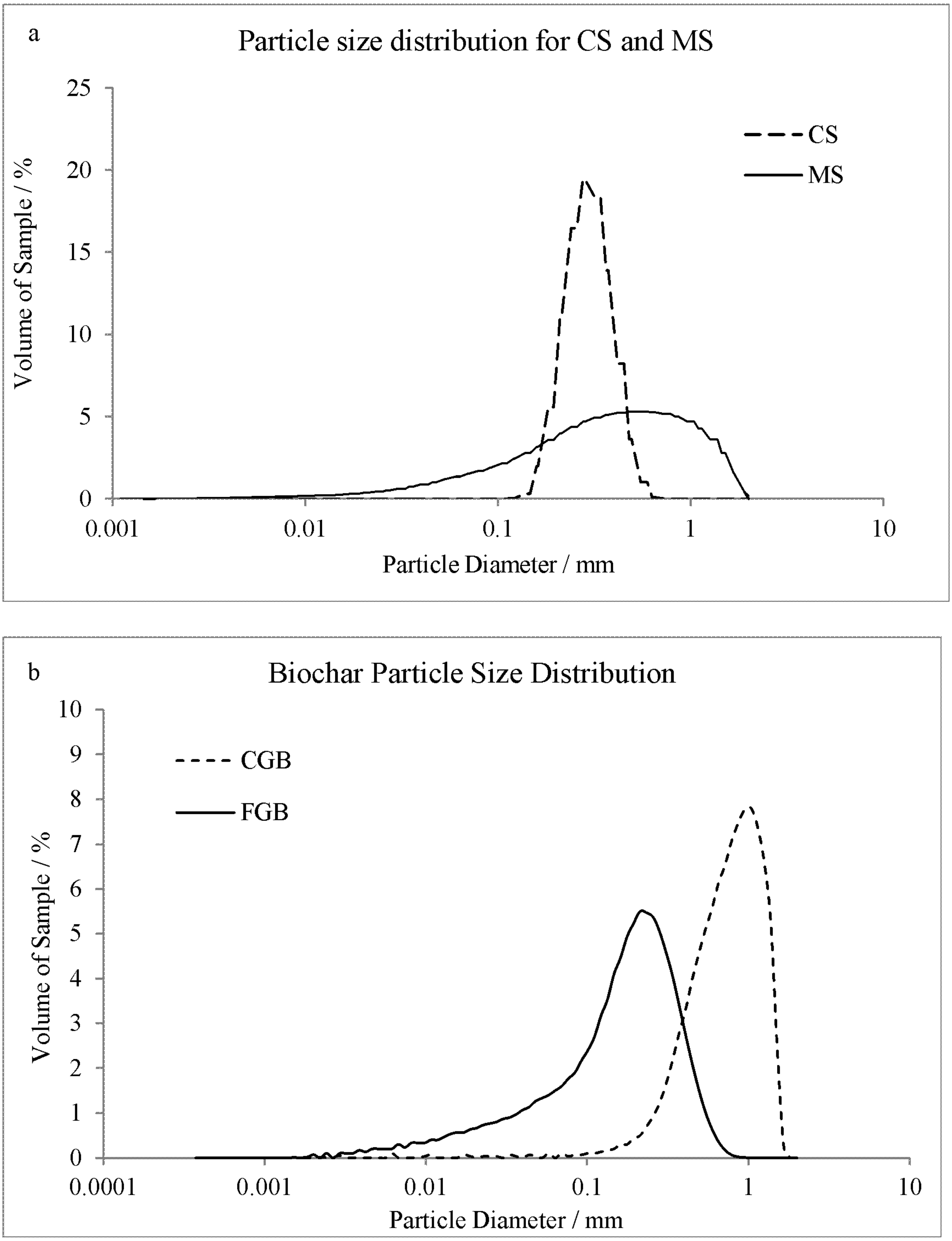
a
Particle size distribution for CS and MS
Volume of Sample / %
25
20
15
10
5
0
CS
MS
0.001
0.01
0.1
1
10
Particle Diameter / mm
b
Biochar Particle Size Distribution
Volume of Sample / %
10
9
8
7
6
5
4
3
2
1
0
CGB
FGB
0.0001
0.001
0.01
0.1
1
10
Particle Diameter / mm

Figure 1.

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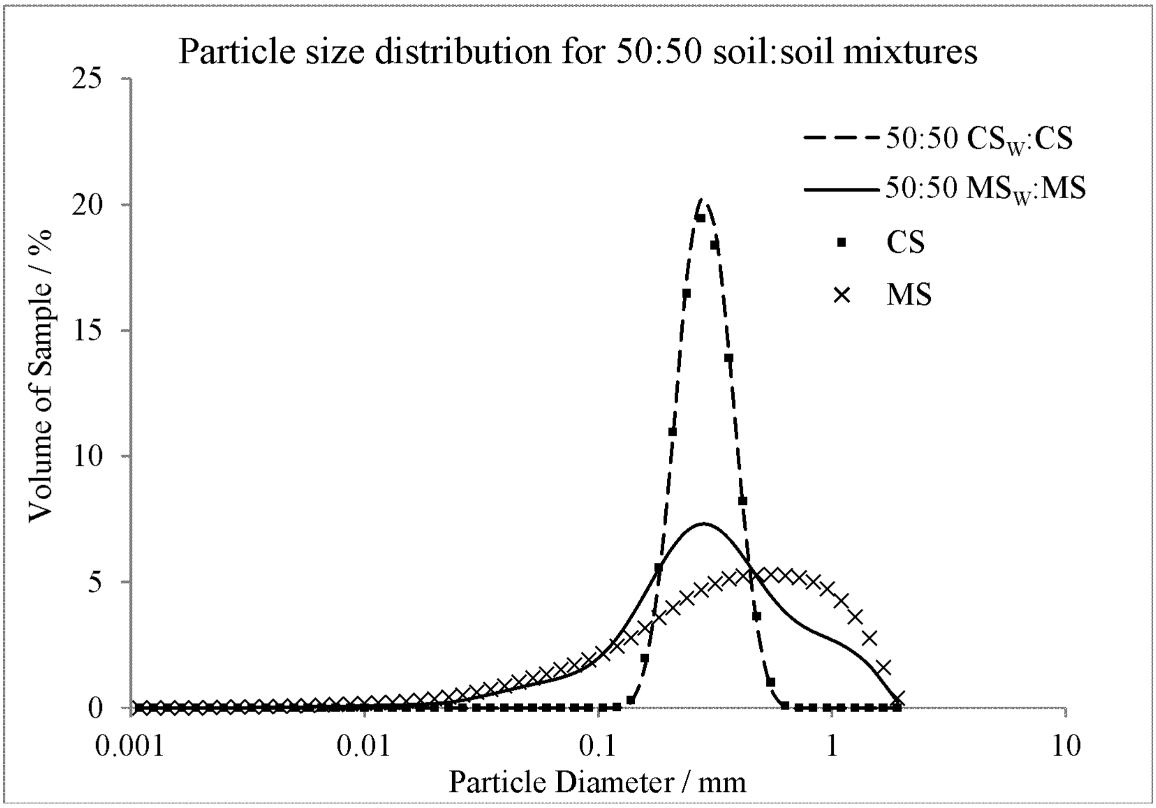

Figure 2.

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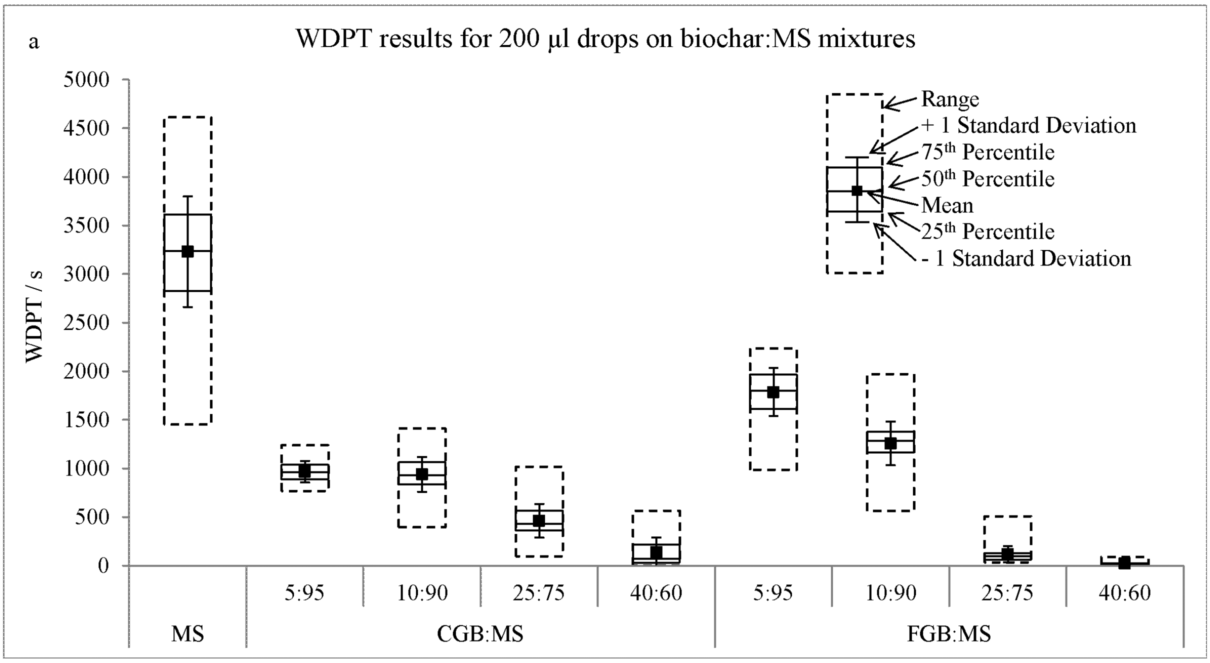

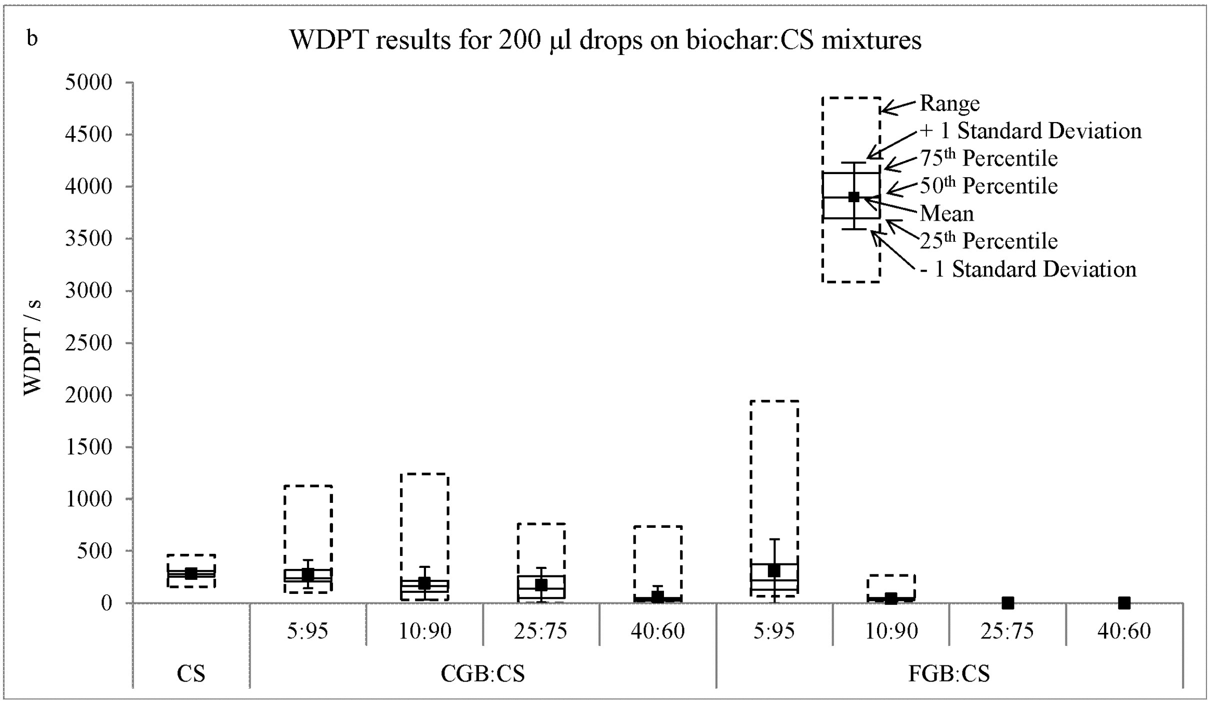

Figure 3.

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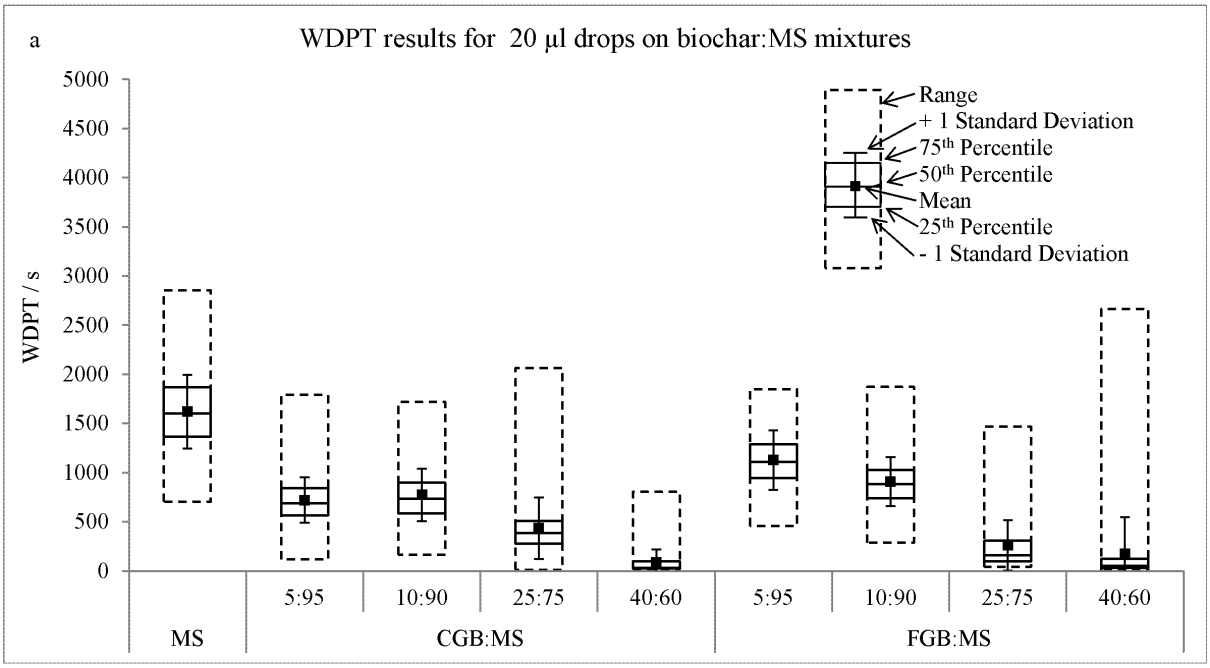

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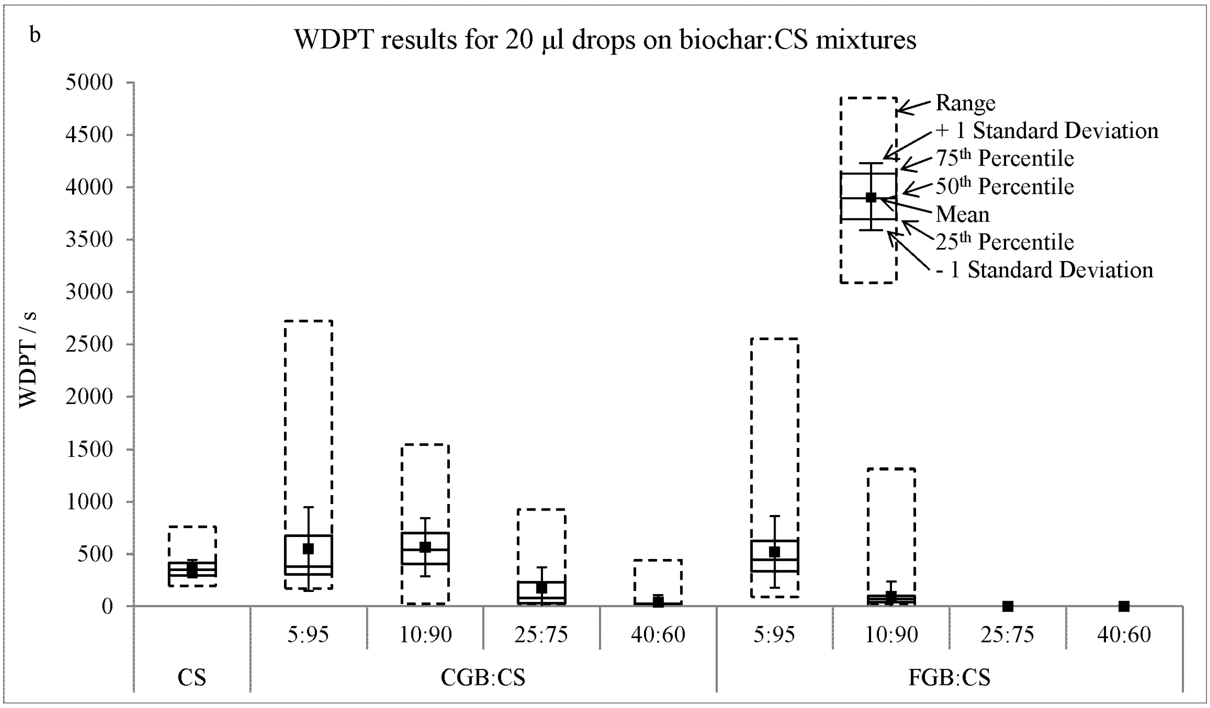
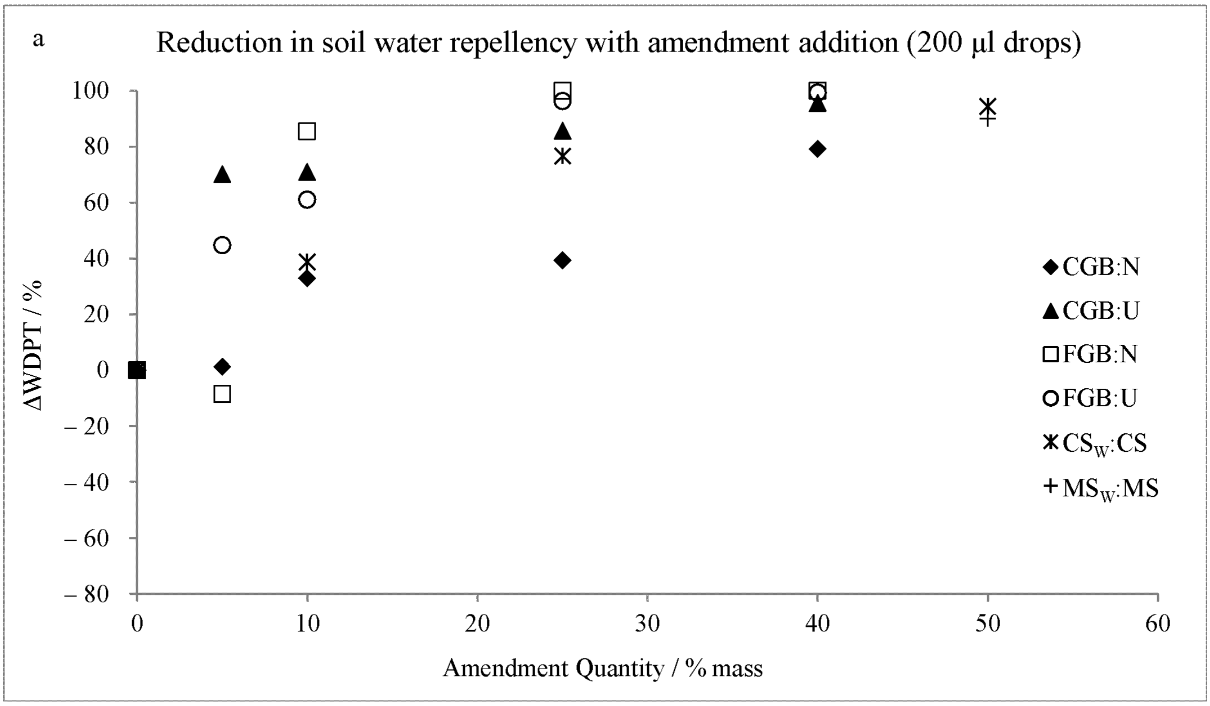


585

586 **Figure 4.**

587


a
Reduction in soil water repellency with amendment addition (200 µl drops)
ΔWDPT / %
100
80
60
40
20
0
– 20
– 40
– 60
– 80
0
10
20
30
40
50
60
Amendment Quantity / % mass
◆CGB:N
▲CGB:U
□FGB:N
○FGB:U
✱CS$_W$:CS
+MS$_W$:MS

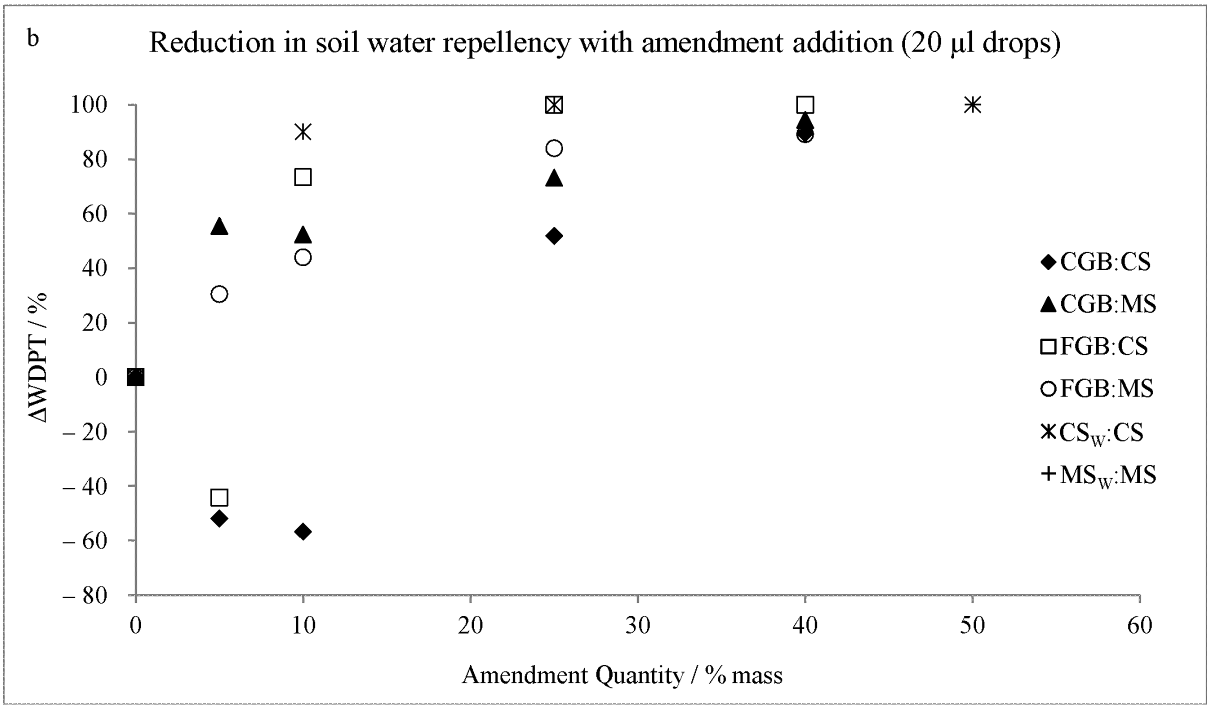

b
Reduction in soil water repellency with amendment addition (20 µl drops)
ΔWDPT / %
100
80
60
40
20
0
– 20
– 40
– 60
– 80
0
10
20
30
40
50
60
Amendment Quantity / % mass
◆CGB:CS
▲CGB:MS
□FGB:CS
○FGB:MS
✱CS$_W$:CS
+MS$_W$:MS

Figure 5.

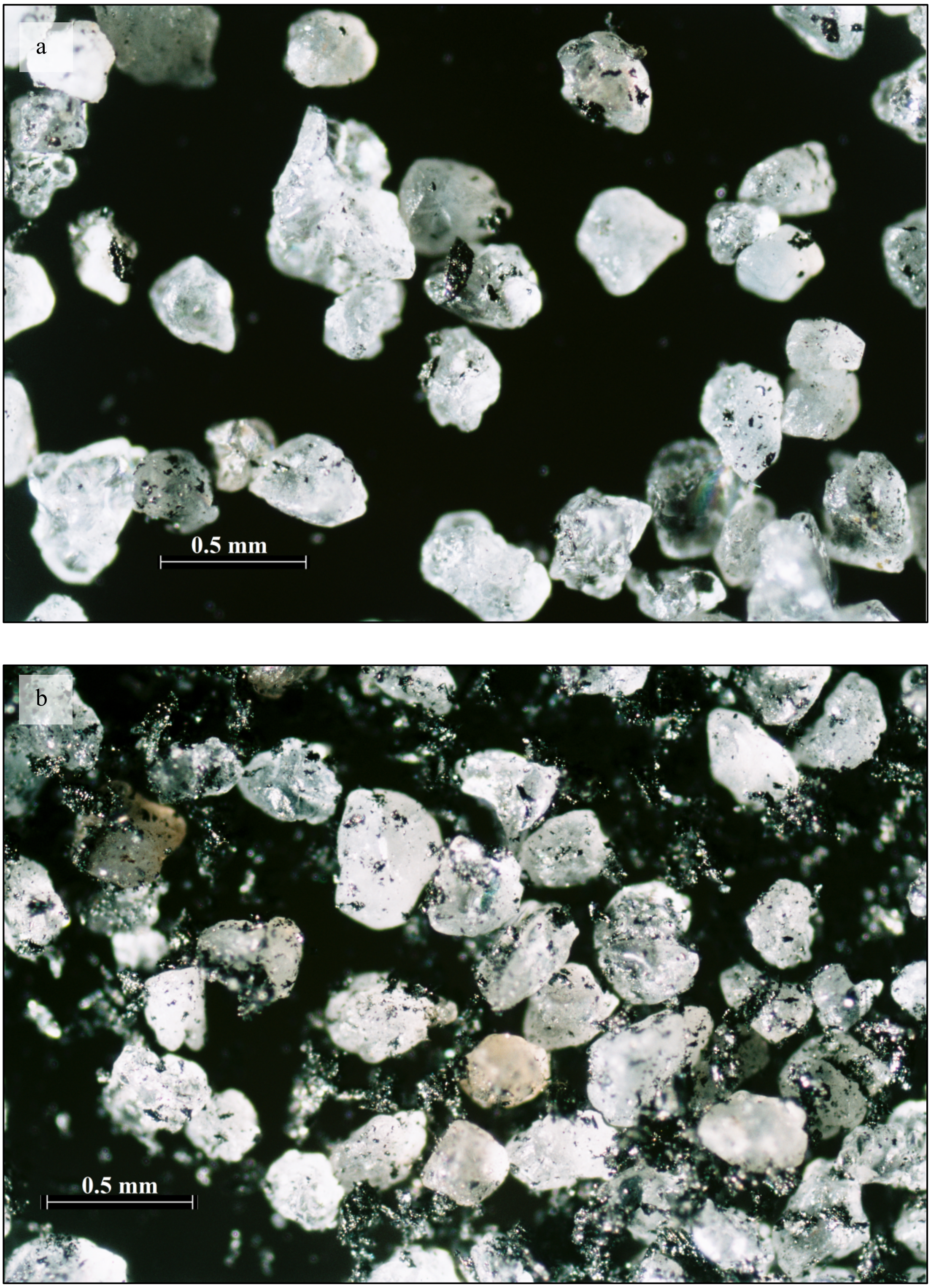


Figure 6.

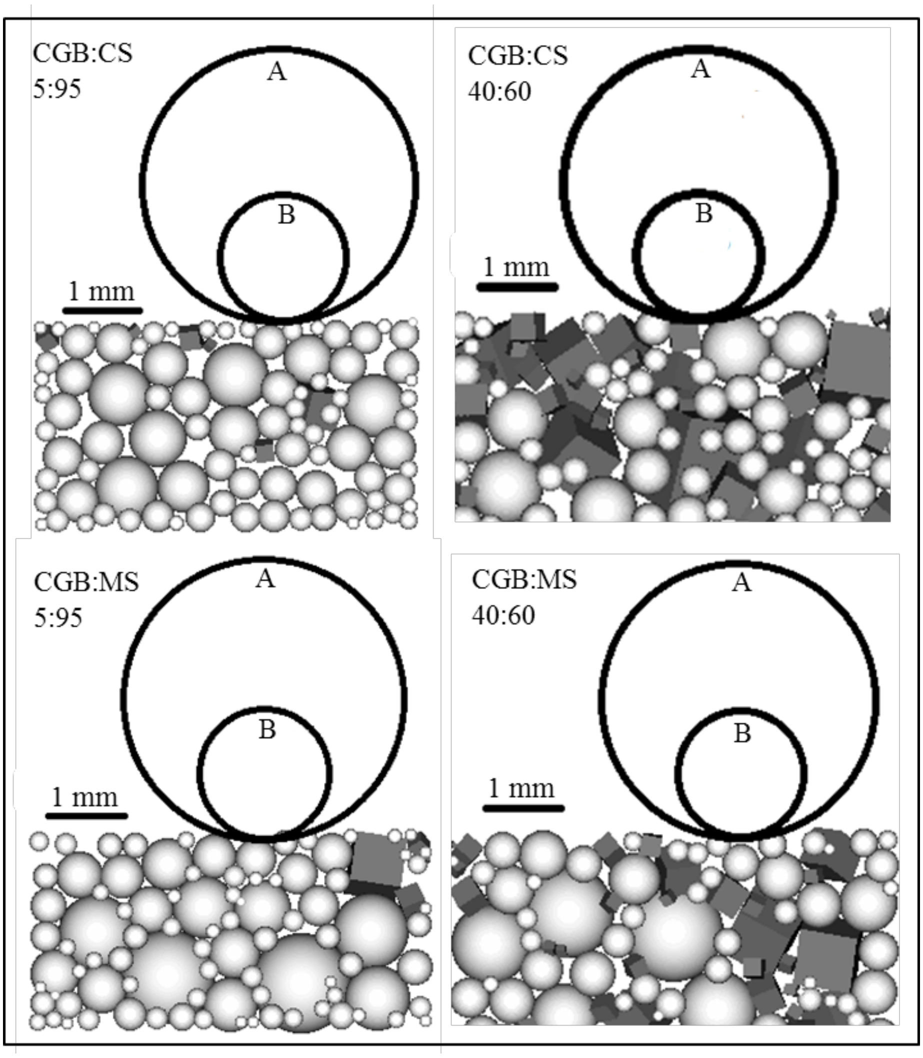

CGB:CS
5:95
A
B
1 mm
CGB:CS
40:60
A
B
1 mm
CGB:MS
5:95
A
B
1 mm
CGB:MS
40:60
A
B
1 mm

Figure 7.