The Effects of Biochar on Hydrologic Properties of Two Contrasting Vancouver Island Podzols

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Contents

Part 1: Introduction

Our society will face significant challenges in coming decades to deal with converging problems of pollution by greenhouse gases (GHGs), nutrients, and industrial byproducts; increased climatic variability (Parry et al., 2007; IPCC, 2012); and human population growth with its attendant problems of land use change, soil and ecosystem degradation (Foley et al., 2005; Braimoh and Vlek, 2008), regional food scarcity (Aggarwal and Sivakumar, 2011), and non-renewable nutrient shortages (Cordell et al., 2009). Biochar (BC) is a low-cost soil amendment that has shown the ability to sequester carbon (C), prevent emissions of GHGs, increase efficiency of land, water, and nutrient use, and improve the condition of degraded or poor-quality soil (Lehmann and Joseph, 2009). This has driven a recent surge in interest for using BC to address these sustainability challenges, which includes the joint research undertaken by the UBC Ecohydrology and Biometeorology & Soil Physics groups to study the effects of BC applications on nutrient retention and GHG fluxes in nitrogen-fertilized forests on Vancouver Island.

My thesis examines some of the possible hydrologic effects of BC soil amendments that could influence the soil processes that are being studied by our research group. I will begin with the basics by introducing the production and properties of BC, before elaborating upon my research goals and their connections to the research being undertaken by the Ecohydrology and Biometeorology research groups. To give context for my experiments I will then present a literature review of similar water-focused BC research, followed by a presentation and discussion of my methods and results, before I conclude with a summary of my results as they relate to the group's research goals.

Introduction to Biochar

Biochar is the term used to describe the high-C products of organic matter (OM) pyrolysis, a process in which biomass is heated with limited aeration (Downie et al., 2009). The lack of aeration prevents oxidation of C to carbon dioxide (CO2), which drives the thermochemical re-arrangement of structural C in OM into stable aromatic hydrocarbons, and causes production of large quantities of volatile gases and oils, which are of greater economic interest (as biofuels) than BC (Downie et al., 2009; Ericsson, 2012).

Although BC commonly is the by-product of biofuel production, it can also be purpose-made as a soil amendment (Novak et al., 2009; Lehmann and Joseph, 2009). BC is highly recalcitrant to biochemical degradation, lasting hundreds or thousands of years in soils, owing to its aromatic C structures (Glaser et al., 2002), which has given it prominence for its potential contributions to climate change mitigation (Woolf et al., 2010). Activated carbon (chemically-treated BC) is a common industrial material for adsorption functions, but it is too expensive to produce as a bulk soil amendment. Therefore, benefits to water and nutrient retention from BC must be realized through its inherent properties, such as high specific surface area, high internal porosity, and high cation exchange capacity (CEC), which are all influenced by the feedstock and pyrolysis conditions of BC production (Downie et al., 2009; Novak et al., 2009; Streubel 2011). A current goal is the development of pyrolysis technologies that enable production of BC optimized for specific uses (Novak et al., 2009).

The feedstock for BC production can be essentially any organic material, though waste products, such as manures, crop residues, and wood wastes, are more economically and ecologically beneficial.[1] The feedstock is the most important determinant of BC physical properties because, despite pyrolization transformations, the physical structure of BC resembles that of the feedstock. For example, angiosperm BC has greater volumes of water-transmitting macropores than gymnosperm BC because of the presence of large xylem vessel elements in the angiosperm vascular system (Downie et al., 2009).

There are also numerous factors during the pyrolization process that affect BC properties. The most important of these are expected to be the highest treatment temperature (HTT), heating rate, and vessel pressure, respectively in order of importance (Downie et al., 2009). BC is typically pyrolized between 250°C and 700°C, with nanoporosity (pores with diameters less than 1 µm) and surface area generally increasing with temperature until an upper limit around 800°C - 900°C (Brown et al., 2006; Downie et al., 2009). HTT may have an effect on BC chemical properties as well, with hydrophobicity being lowest in BC produced between 400°C and 600°C (Kinney et al., 2012). The potential for BC chemical properties to change over time in the soil must also be recognized. Changes to BC occur as ash and hydrophobic materials are leached and oxidized over the first months to years (DeBano, 2000), and over the longer term as soil surfaces oxidize and bind with OM and fine soil particles, which may further enhance CEC and water retention properties (Glaser et al., 2002). Therefore, effects on hydrologic properties that I find with fresh BC may not be relevant over the long term.

[1] However, extensive use of crop residues and manures for fuels has been justifiably questioned from the perspective of depletion of labile OM and nutrients from soils (Lal, 2005; Tan et al., 2005).

Biochar research by the Ecohydrology and Biometeorology groups

The government of British Columbia has identified increasing C sequestration in the province's forests as a climate change mitigation goal (Greig and Bull, 2009), which research by the Biometeorology group showed can be accomplished by nitrogen (N) fertilization of forests on Vancouver Island (VI) to increase carbon uptake via vegetation growth (Jassal et al., 2008). Follow-up studies indicated that the GHG-balance benefits of N fertilization could be strongly improved by minimizing gaseous loss of nitrous oxide (N2O), a very potent GHG (Prather and Ehhalt, 2001). N2O losses account for approximately 5% of field-applied N at the VI study site (Jassal et al., 2008), and effectively nullified more than half of the first-year GHG-balance improvements by C uptake (Jassal et al., 2010). In numerous other studies BC has been demonstrated to control emissions of N2O (Singh et al., 2010; Taghizidae-Toosi et al., 2011) and methane (CH4) (van Zwieten et al., 2009), another potent GHG (Prather and Ehhalt, 2001). Therefore, the Biometeorology group's latest research is investigating possible benefits of BC for reducing GHG emissions and fertilizer losses, and increasing tree growth in a fertilized VI site.

Relevance of this research

My project will contribute to the research agenda outlined above by studying how BC affects the hydrologic properties of soil from the Campbell River (CR) study site. Specifically, I will look at the effects of varying rates of BC application on water retention (WR) properties and saturated hydraulic conductivity (Ksat) of these soils. From my WR results I intend to calculate plant-available water-holding capacity (AWC), porosity drained at field capacity (FC), and indicators of macroporosity. Knowledge of these hydrologic properties of BC-amended soils is highly relevant to the group's nutrient retention and GHG studies, as explained below.

Soil water is inextricably linked to ecosystem nutrient fluxes. At the most fundamental level, plants cannot uptake nutrients without water as the solvent, and do not use nutrients without water to fuel photosynthesis (Taiz and Zeiger, 2006). Given the summer seasonal drought that affects eastern VI, improvements in AWC should allow increased use of nutrients, thus preventing dissolved or gaseous losses of these nutrients from the soil solution and increasing photosynthetic C uptake.

Furthermore, the behavior of soil water determines the rate of nitrate (NO3) leaching, which is a major management concern because the CR site's coarse soils are unable to retain large reserves of nutrients, which increases risks for downstream ecosystems and limits potential fertilizer benefits. My

Ksat experiments are relevant to NO_3 leaching because the rate at which water flows through the soil indicates the rate at which soil solution constituents may be lost by leaching after precipitation. Changes detected in macroporosity and drainable porosity indicate possible changes to the volumes of soil solution quickly lost from the rooting zone following a precipitation event.

Finally, water saturation is the cause of anoxic, reduced conditions in the soil that lead to N_2O and CH_4 emissions (Brady & Weil, 2007). Since these gases have global warming potentials 298 and 25 times stronger than CO_2, respectively (Prather and Ehhalt, 2001), minimizing their emissions from CR soils is a major goal. This will occur if anoxic conditions are minimized temporally and spatially through improved soil drainage, which I will look for in my Ksat tests and in my calculations of drainable porosity and macroporosity based on WR tests.

Part 2: Theoretical Background and Literature Review

Water Retention Theory

A soil's water retention characteristics are dictated by its surface area and pore structure. Surface area in a soil is a product of its particle size distribution, mineralogy, and OM content. Specific surface area increases exponentially as particle size decreases, giving clays surface areas thousands of times greater than sands (Brady and Weil, 2007).

The total porosity of a soil determines how much water a saturated soil holds, but this is far less important than the size and geometry of those pores, which determine how much of the retained water will be available to plants. From the capillary equation, we know the tension, *T*, with which water is retained in pores is determined by pore radii, *r*, and the solid-liquid contact angle, α (Equation 1; Appendix A). In most soils α is not of concern (Brady & Weil, 2007), but it could have influential effects in a soil amended with hydrophobic BC.

Equation 1. $$\boldsymbol{T \propto \frac{\cos\alpha}{r}}$$

Assuming cylindrical pore geometry , approximate conversions can be made between tensions and effective pore radii using Equation 2, where *D* is the effective pore diameter (in µm) and Ψ is soil water potential (in kPa) [2] (Brady and Weil, 2007; explained in Appendix A).

Equation 2. $$\boldsymbol{D = 300\,\Psi^{-1}}$$

A common distinction is made between micropores and macropores (diameter > 60 - 80 µm, equivalent soil water potential = 4 kPa) (Bouma, 1981; Brady and Weil, 2007). Macropores conduct water rapidly in response to gravity, facilitating soil aeration. Coarse-textured soils are dominated by macropores between sand grains, and thus lose their water relatively easily compared to micropore-dominated fine-textured soils (Beven and Germann, 1982).

Water moves through a soil in response to gradients in potential energy (Hillel, 1998). Aside from gravity-driven flow through exceptionally large pores, there are essentially two simultaneous processes of water flow in a soil: some water moves by capillarity through larger pores, while some

[2] $\Psi = -\mathrm{T}$, where *T* is tension. I will often use tension equivalents to minimize confusion with negative signs

water moves slowly as a film across soil surfaces (Tuller and Or, 2004). The balance between the two processes in a soil is based on its pore size distribution, but at tensions beyond 100 kPa essentially all water in a soil is adsorbed and only moves as a film (Tuller and Or, 2004).

As soil water content decreases so does the potential energy of the soil water, which eventually becomes so low at the permanent wilting point (PWP, approximated at 1500 kPa) that plants roots cannot generate sufficient osmotic gradients to obtain water. Therefore, the most important aspect of WR for plants is the volume of water that is released to plants between gravity-drained FC and PWP, which is called the available water capacity (AWC) of the soil.

From the perspective of nutrient cycling, another important WR measurement is the pore volume drained between saturation and FC, which represents potential leachate volume and indicates soil aeration characteristics. Each soil exhibits its own characteristic FC tension, related to varying matric potentials in soil bodies due to differences in texture and OM content, pore size distribution, and specific surface area of surrounding soils (Skopp, 2005). Therefore, coarse-textured soil FC is approximated at 10 kPa and fine-textured FC at 33 kPa (Skopp, 2005; Brady and Weil, 2007). A similar measurement can be made using gravity-drained soil columns, which, lacking underlying soil, will retain more water than at FC. The approximate tension at a gravity-drained state is 5 kPa, meaning that the drained pores have effective diameters of ~60µm and can approximate the macroporosity of a soil (Brady and Weil, 2007).

Application of BC may have beneficial effects on AWC by increasing porosity and surface area of soils, since the surface area of BC is comparable to that of clay particles (Downie et al., 2009). However, the majority of BC surface area occurs in internal pores smaller than 2nm (Downie et al., 2009), which is far too small to contain AWC (equivalent tension = 150000 kPa), so it seems that the benefits of BC may be more strongly related to its particle size. Finely-crushed BC will contain more of its surface area on external surfaces, thus behaving more like a clay particle, whereas coarse BC particles may behave like sand in regards to the creation of packing void macropores around particles (Gupta and Larsen, 1972; Downie et al., 2009).

Biochar’s Effects on Water Retention: Literature Review

I have focused my review on studies with similar coarse-textured soils. Although it would have been ideal, it has not been possible to look only at BC made with gymnosperm wood because of a lack of research. However, I have avoided studies of BC from materials like manures and pulp sludges due to their strong dissimilarities from wood BC (Downie et al., 2009). I have created a spreadsheet documenting the details of papers that I have reviewed that may be useful for other research undertaken by the group (Appendix B).

There is a growing body of literature documenting the effects of BC on soil hydrologic properties, but there are serious research gaps that remain to be addressed (Kinney et al., 2012). For example, little is quantitatively known about the structure of BC pores larger than 50 nm even though these are the only important pores from a water movement perspective (effective pore diameter for fluid conductivity > 9100 nm (33 kPa); see Ksat Literature Review section) and a plant-availability perspective (equivalent pore diameter at PWP is ~200nm) (Kinney et al., 2012).

Methodological inconsistencies in the literature

In performing this literature review it has become clear that comparisons between studies can be questionable due to inconsistencies in methods and data reporting. There are nearly as many methods of measuring WR as there are papers on the subject. The most popular method is the pressure plate apparatus, but this is done over an inconsistent range of tensions (Gaskin et al., 2007; Laird et al., 2010; Brockhoff et al., 2010; Streubel et al. 2011). Some studies use pressure cells at low tensions (< 30 kPa) before switching to pressure plates to obtain a better characterization of the low tension water-release curve (Laird et al., 2010; Brockhoff et al., 2010). Other methods include: computer modeling of WR curves using pressurized outflow tests (e.g. Kameyama et al., 2009; Uzoma et al., 2011); logged field measurements of volumetric water content (VWC) and matric potential (Major et al., 2012); and measurement of leachate volume from columns (Bell and Worrall., 2011). Some studies have determined gravimetric water content (GWC) differences in freely-drained columns or pots, without regard for the effects of soil packing and bulk density differences that determine the plant-availability of this water (Dugan et al., 2010; Busscher et al., 2010).

Soil and BC particle size distributions are highly influential on WR characteristics, but are reported inconsistently or not at all, especially for BC (e.g. Brockhoff et al. (2010) describe their BC as "powdery"). Where reported, sieving of BC has been done to various sizes between 0.18 mm and 0.5 mm for pressure plate tests (Novak et al., 2009; Laird et al., 2010; Uzoma et al., 2011), and ranges up to 6 mm for pot-based tests (Busscher et al., 2010).

Packing of soils is an important preparation step that is also underreported. Packing all treatments to equal bulk densities is the common practice (e.g. Gaskin et al., 2007; Busscher et al., 2010, Uzoma et al., 2011) despite the improbability of a BC-amended soil showing equal bulk density as a non-amended soil, and differences in porosites of treatments with different contents packed to equal bulk density (see Appendix C and Results section).

While some studies report BC application rates in metric tonnes per hectare (T/ha or Mg/ha), others report it on a weight-basis (e.g. Busscher et al., 2010) or volume-basis (e.g. Brockhoff et al., 2010). Conversion is simple if bulk density and incorporation depth are provided, but this is not always the case (e.g. Gaskin et al., 2007; Busscher et al., 2010). This is simple data for authors to provide that facilitates use of their results. I will report treatments in T/ha and on a weight basis (g of BC per kg soil) wherever possible. My equation for converting between these two rates is derived at the end of Appendix C.

Review of other studies

On the coarsest end of the spectrum, I found two studies using BC in nearly pure sands. Brockhoff et al. (2010) used switchgrass BC at rates from 13 T/ha (5 g/kg) to 74 T/ha (31 g/kg) and found that AWC significantly increased ($P<0.001$) by 16-240% with increasing BC content, with increased VWC at saturation and FC but not at PWP. The other study, which used angiosperm wood BC at 10 T/ha (4.5 g/kg) and 20 T/ha (9 g/kg), showed significant increases ($P<0.05$) in AWC for all treatments relative to control soils (Uzoma et al., 2011). Most of the differences in Uzoma et al.'s (2011) treatments occur in the low tension range below 100 kPa, indicating that differences in pore structure of amended soils caused the AWC improvements rather than surface area increases (Tuller and Or, 2004). Differences between HTTs of 300°C, 400°C, and 500°C were significant in some cases, with 500°C showing the highest AWC (Uzoma et al., 2011).

In finer textured soils, results become much more inconsistent. Gaskin et al. (2009) amended a loamy sand agricultural soil with BC from various rural byproducts, including pine chips, at rates between 11 and 88 T/ha, but only found significant increases in VWC at any tension with one feedstock at the highest application rate, which is too high for practical field applications (Uzoma et al. (2011) suggest 20 T/ha as an upper practical limit). There was no significant difference (NSD) in VWC at any tension with pine chip BC.

In Novak et al.'s (2009) experiment with gravity-drained pots of loamy sand amended with BC from three agricultural wastes at the relatively high rate of 40-44 T/ha (20 g/kg), all feedstocks showed higher mean GWC (increases up to 0.16 g/g soil), but only three treatments out of six showed significant differences over control soils ($P<0.05$). There was NSD between HTT of the feedstocks (Novak et al., 2009). Also on a gravity-drained, gravimetric basis, Dugan et al. (2010) found that finely-sieved sawdust BC applied at 5 T/ha (2.4 g/kg), 10 T/ha (4.9 g/kg), and 20 T/ha (7.3 g/kg) achieved statistically equal 349-481% improvements in a loamy sand's gravity-drained water content. However, a different wood char yielded benefits of 36% at 5 T/ha, but water contents at 10 T/ha and 20 T/ha were unexpectedly significantly less than the 5 T/ha treatment. This anomaly is attributed to hydrophobic materials in this BC becoming dominant on particle surfaces at higher rates (Dugan et al., 2010).

A very relevant study was undertaken in Washington State recently using two types of Douglas Fir BC (from wood pellets and from bark) on five soils that range in texture from sandy to silt loam (Streubel et al., 2011). Their results provide a good demonstration of the complex interaction between soil type, BC type, and application rate in determining water retention effects. Their results with a sandy soil (~85% sand) at BC rates up to 39 T/ha (15 g/kg) showed NSD from the control VWC at 100 kPa, which seems to run contrary to the studies above, but Streubel et al. (2011) did not test WR at FC to look for the differences in VWC at low tension that were described by Uzoma et al. (2011). Despite there being NSD in VWC between treatments with the sandy soil, significant increases were observed in 4 silt loam soils at 100 kPa. The authors attribute their variable results between sandy and loamy soils to the sandy soil's coarse texture, which made it difficult to pack uniformly. Bark BC showed higher WR than pellet BC. Contrary to expectations, pellet BC caused NSD in the low-clay silt loams, but significantly improved WR in the high-clay silt loams, showing the unpredictability of BC effects on soil pore structure and WR properties.

Saturated Hydraulic Conductivity Theory

Darcy's Law describes the flow of water through a soil as a response to water potential differences ($\Delta\Psi$) that exist between the ends of a soil column of length, *L*, and perpendicular cross-sectional area, *A*. The flow rate, expressed in volume of water, *Q*, per unit time, *t,* at a given water potential gradient is controlled by the soil's ability to conduct water , which is described by its *Ksat* constant in saturated conditions and the variable *Kunsat* in unsaturated conditions (Equation 3) (Hillel, 1998).

Equation 3 $$\frac{Q}{t} = A \cdot Ksat \cdot \frac{\Delta\Psi}{L}$$

According to Poiseuille's Law, flow rate through a tube is proportional to the fourth power of its radius, which makes it clear that large pores are the dominant contributors to the flow of water through soils (Hillel, 1998), as demonstrated in field studies (Cameira et al., 2003; Table 1). In an unmanaged soil, Ksat is dominated by flow through root channels, biopores created by soil fauna, and packing voids that are greater than 1 mm in diameter (Beven and Germann, 1982; Sobieraj et al., 2002; Brady and Weil, 2007). However, at least the former two classes of macropores will not be present in my study of repacked columns. Tortuosity, connectivity, and shape of pores are other determinants of flow rates in soils, reflected by increased flow through well-connected, linear pore systems (Hillel, 1998).

Macropore Size Class (mm)	% of Pore Volume	% of Flow
>0.5	2.725	84.25
0.25-0.5	1.35	9.5
0.1-0.25		3
TOTAL:	**4.075**	**96.75**

Table 1. Macropores occupy a small volume but conduct almost all of the flow in saturated conditions in a silt loam (from Cameira et al., 2003).

It is common to describe porous fluid-conducting media in terms of total and effective porosity, with effective porosity excluding poorly-connected and small pores that do not significantly contribute to conductivity (Koponen et al., 1997). Ahuja et al. (1984, 1989) showed that saturated hydraulic conductivity can be estimated from the effective porosity of a soil, which they defined as the volume of pores drained between saturation and -33 kPa using a pressure plate. This apparent relationship between effective porosity and Ksat may be useful because Ksat is one of the most variable soil properties to measure, with expected coefficients of variation (CV) of 75-150% (Pennock, Yates and Braidek, 2006). Also, the high water requirements for field testing of Ksat are prohibitive. On the contrary, many WR cores can be taken with relatively little effort and run simultaneously in the lab.

Biochar's Effects on Saturated Hydraulic Conductivity: Literature Review

The effects of BC application on hydraulic conductivity have not been studied as thoroughly as water retention, so there is a smaller pool of papers to draw from. This can likely be attributed to high variation in Ksat results of field-collected soils, and the questionable applicability of repacked columns to field situations. In the Ksat literature, there are again inconsistencies in methods reporting of experimental details. The literature review is again summarized in Appendix B.

From the theory described above it is clear that we would expect the Ksat of coarse soils to decrease with the addition of fine particles and consequent decrease of macroporosity. Thus, Brockhoff et al. (2010) found that switchgrass BC added to sand at rates between 13 T/ha (5 g/kg) and 74 T/ha (31 g/kg) caused significant 34-92% reductions in Ksat ($P<0.05$). Although Uzoma et al.'s (2011) sand was actually finer than Brockhoff et al.'s (2010), Uzoma et al. (2011) found stronger Ksat reductions (76% and 92%) at comparatively low BC rates (10 T/ha (4.5 g/kg) and 20 T/ha (9 g/kg)).

Packing theory suggests that such strong Ksat reductions will not occur in most natural soils (i.e. those that are not almost pure sand) because of the diversity of pore sizes and reduced macroporosity in soils that have more diverse particle sizes (Gupta & Larsen, 1979). In other words, Ksat alterations with BC amendments seem to occur because of changes to the soil pore size distribution more than because of BC properties. This emphasizes the importance of BC preparation (crushing and sieving) on experimental results. Supporting this idea, Busscher et al. (2010) actually found *increased* infiltration rates ($P<0.05$) in loamy sands amended with coarsely-sieved (<6 mm) BC at rates between 6 T/ha (5 g/kg) and 24 T/ha (20 g/kg). Busscher et al's (2010) results showed NSD ($P<0.05$) between the widely-varied amendment rates, suggesting that high Ksat effects may be achieved at relatively low BC rates.

In Ksat experiments that have been done in fine-textured soils that are naturally dominated by microporosity, it is not surprising that many cases of Ksat increases have been found with BC application. However, these increases are inconsistent, and seem to require high rates of BC – anywhere from 16 T/ha (Asai et al., 2009) to 97.5 T/ha (Kameyama et al., 2010).

Part 3: Materials and Methods

Study Site and Soils

Soils for this study came from the CR flux tower site, a recently clearcut Douglas Fir stand near Campbell River on the east coast of Vancouver Island. Pre-harvest site and soil characteristics are described in detail by Drewitt et al. (2002). The site's soil has been classified as a Duric Humo-Ferric Podzol of the Quimper association (Jassal et al., 2011). Quimper soils are gravelly loamy sand to sandy loam in texture, which makes them relatively well-drained, with OM content varying by edaphic setting (Chatterton et al., 1981; Jungen, 1986). All soils were collected from between 10 and 20 cm depth, in order to avoid maximum OM concentrations while still reflecting topsoil characteristics. At 10-20 cm depth, the site's mean soil bulk density is 1352 $\pm$ 51 kg/m^3 ($\pm$1 standard error), while topsoil (<10 cm depth) bulk density is estimated at 971 $\pm$ 221 kg/m^3 (Drewitt et al., 2002). For water retention experiments, soil was collected from two locations. The first location was in a relatively flat area (~10 m^2) in the sloping clearcut, whereas the second location was slightly elevated and well-drained, which yielded two contrasting soils for the study, denoted from herein as 'Soil O' (organic) and 'Soil M' (mineral), respectively. These soils were air-dried and sieved to 2 mm for the WR cores. Soil M was the only soil used for the Ksat experiment, for which it was air-dried and sieved to 5 mm.

Particle size distributions of both soils' fine (< 2mm) fractions were tested using the 'rapid method' introduced by Kettler et al. (1999). Although this method requires minimal time and simple equipment, results from the rapid method have correlated better to the pipette method, which is considered the most accurate and precise particle size analysis method, than those from the hydrometer method (Kettler et al., 1999). The rapid method is performed on a 15 g soil sample dispersed with sodium hexametaphosphate. The first step is wet sieving on a 53 µm sieve to separate sand from silt and clay, followed by sedimentation to separate silt from clay. The settling time for silt in my experiment was 120-130 minutes. Next, the clay suspension is decanted from the silt, and silt and sand contents are determined by oven-drying. In the standard procedure, the clay suspension is disposed of and the clay weight is determined by difference. I decided to collect a subsample of a Soil O clay suspension to determine the OM concentration of the brownish-red slurry, but clay content was still calculated by difference. Sub-samples from the oven-dry soil fractions (sand, silt, and clay) had their OM content determined using the loss-on-ignition method at 600 °C for 16 hours (Nelson and Sommers, 1996). The particle size and OM tests were performed in duplicate for each soil, except OM tests for clay, which were done with only one subsample. An analysis of the coarse particles in the Ksat soil (Soil M) was done by dry-sieving crushed soil using stacked 2-mm and 0.991-mm sieves.

Soil particle density was not directly determined. Instead, a volume-weighted particle density for each soil was calculated using the data from my OM tests and Equation 4 derived below (where $\%_{OM}$ is the percent weight of dry OM per unit dry soil; $\rho_{p\ soil}$ is the combined soil particle density; M , V , and ρ are the mass, volume, and particle density, respectively, of the denoted subscript quantity; $\rho_{om} =$ 1300 kg/m^3, ρ_{min}= 2650 kg/m^3).

$$\rho_{p\ soil} = \frac{M_{soil}}{V_{soil}} = \frac{M_{OM} + M_{mineral}}{V_{OM} + V_{min}} = \frac{M_{OM} + M_{min}}{\frac{M_{OM}}{\rho_{OM}} + \frac{M_{min}}{\rho_{min}}} = \frac{\%_{OM} + (100 - \%_{OM})}{\frac{\%_{OM}}{\rho_{OM}} + \frac{(100 - \%_{OM})}{\rho_{min}}}$$

Equation 4
$$\boldsymbol{\rho_{p\ soil} = \frac{100}{\frac{\%_{OM}}{\rho_{OM}} + \frac{(100-\%_{OM})}{\rho_{min}}}}$$

Biochar Properties

Biochar for this study was provided by Diacarbon Energy Inc. The Douglas-fir (*Pseudotsuga menziesii*) feedstock was pyrolized at a relatively constant 400 – 420°C for 32 minutes, yielding a BC product containing 78.8% fixed C, 18.8% volatiles, and 2.4% ash by mass, with the balance being adsorbed water (Personal communication (e-mail), Kelly Sveinson, Langara College, October 20, 2011). For the WR study, BC was sieved to 2 mm. Elongated BC pieces in excess of 5 mm were able to pass the 2-mm sieve with vigorous shaking, so the passed BC was re-sieved three times with light shaking to retain the coarsest fragments (7.3% by mass). Biochar for the Ksat experiment was sieved to 5 mm to exclude only the coarsest particles (1.9% by mass).

Biochar particle size analysis was performed using stacked dry sieves (53, 105, 425, 991, and 2000 µm) that were stirred and shaken by hand for 5 minutes to accelerate the separation process before being put on a mechanical shaker for 65 minutes. A large amount of BC (133.15g) was used to minimize any effect on results from fine BC dust that adhered to sieve surfaces.

Biochar particle density was determined using distilled water-filled pycnometers (Blake and Hartge, 1986). The first attempt using a full size assortment of 2 mm-sieved BC did not work because the finest BC particles would remain floating at the surface of the pycnometer fluid. This caused BC to be lost in overflow when the pycnometer stopper was inserted and during the preceding boiling process.

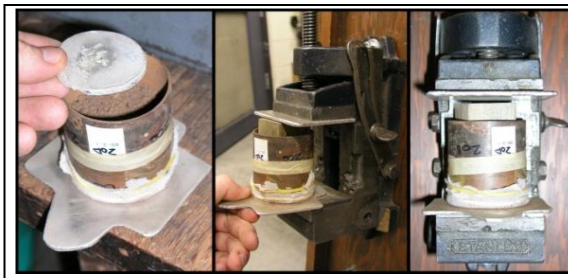
Therefore, a second run was done using BC only from the 0.991– 2 mm size class. This BC absorbed water and sank readily, which allowed particle size to be determined as one would with a mineral soil sample. BC was allowed to stand in the fluid-filled pycnometers (*n* = 4) for 4 hours, before being gently boiled for 10 minutes to facilitate de-aeration. Then the pycnometers were allowed to cool to room temperature before final measurements were taken.

Water Retention Experiments

Pressure Plate

The pressure plate experiments were carried out with repacked cores using a Soil Moisture Co. 1600 5 Bar Ceramic Plate Extractor. Klute's (1986) procedure was followed with slight modifications. The same cores were tested at multiple tensions by reseating cores on pressure plates that had been misted with water to ensure good hydraulic contact between plate and soil pores. Plates and cores were saturated with 0.001M $CaSO_4$ solution to simulate soil solution chemistry, but this solution was not de-aerated.

Soils were packed into metal rings covered on one end with cotton gauze using a vertically-mounted vise (see Box 1). For Soil O, two ring sizes were used. Two replicates were packed in 60.2mm-diameter rings that ranged from 28.5 to 31.0mm high, while the other three replicates were packed in 53.8mm-diameter rings that ranged from 29.2 to 30.0mm high. Soil M was packed into 47.5mm-diameter rings ranging from 18.8 to 19.1mm high.



Box 1. Soils were filled into two rings taped together. An aluminum piston was pressed down by a piece of wood inside a vertically-mounted vise. The vise's top and bottom plates were replaced with larger aluminum plates to accommodate the rings. The lower plate was moveable. Desired soil column heights were measured with digital calipers.

Soil O was tested at pressures of 0, 5, 10, 33, 44, 62, 76, 95, 128, 200, 300, and 483 kPa. Due to time restraints, the other soil was not measured at the exact same pressures but was tested over the same range of pressures. Soil M was tested at 0, 10, 33, 44, 86, 165, 293, and 483 kPa. Cores were determined to have come to equilibrium when the ring weights changed by less than 0.03 g in a 24-hour period (a VWC difference less than 0.001 m^3/m^3).

In both WR experiments, a control soil was tested against 3 BC rates (*n*=5). The packing goal was to give all treatments equal total porosity to the unamended soil (Appendix C). In the experiment with soil O, the treatments were 0, 5, 10, and 50 T/ha [3] (*n*=5), which required 0, 3.0, 6.1, and 30.3 grams of BC per kilogram of soil, respectively, based on an unamended soil bulk density of 1100 kg/m^3 and incorporation depth of 15 cm (Appendix C). The unamended bulk density of 1100 kg/m^3 was selected after 1300 kg/m^3 was attempted with the control soil and was rejected for being far denser and harder than the field soil. All treatments swelled significantly when saturated (see Results). The Soil O cores had their surfaces covered by fungal growth within days of saturation (Figure 1), which necessitated re-wetting them from the bottom with a Thymol solution (from Ecohydrology supplies, 1 drop per 50 mL), which successfully inhibited growth. Subsequent destructive sampling of cores showed these growths penetrated no more than 2-3 mm from the top surface.

Figure 1. Soil O cores showing fungal growths 1 week after saturation.

In the experiment with soil M, I decided to increase application rates to 0, 10, 50, and 100T/ha in observance of apparently minimal differences seen between the lower treatments (< 10 T/ha) in the initial run with Soil O [3]. This proved to be a mistake because subsequent adjustments of the first run's bulk density calculations revealed much stronger differentiation between the three treatments (Appendix D).

Soil M treatments [4] were packed with a target porosity equal to that of an unamended soil at 1300 kg/m^3. At this bulk density and an incorporation depth of 15 cm, 10, 50, and 100 T/ha translated to 5.1, 25.6, and 51.3 g of BC per kg of soil. All samples swelled upon saturation and shrunk thereafter.

Calculations

IN calculations involving FC (e.g. AWC, gravity-drained porosity), I have used 10 kPa for Soil M and 33 kPa for Soil O as the FC approximations in accordance with Skopp (2005). At the high tension end of the AWC range I have had to settle for 483 kPa as my lower limit instead of the accepted PWP standard of 1500 kPa because the 15-bar pressure extractor is not operational.

[3] Soil O treatments 0, 5, 10, and 50T/ha will be referred to as O0, O5, O10, and O50, respectively.

[4] Soil M treatments 0, 10, 50, and 100T/ha will be referred to as M0, M10, M50, and M100, respectively.

Plant-available water capacity (AWC)

AWC is the volume of water released between FC and PWP (Equation 5).

Equation 5 $$\boldsymbol{AWC = VWC_{FC} - VWC_{PWP} = VWC_{10\ or\ 33kPa} - VWC_{483kPa}}$$

Pore volume drained at FC

The pore volume that is drained at FC (θ_{FC}) is calculated as the difference between VWC at saturation and FC, as shown in Equation 6, where the FC tension is 10 kPa for Soil M and 33 kPa for Soil O.

Equation 6 $$\boldsymbol{\theta_{FC} = VWC_{0kPa} - VWC_{FC}}$$

Macroporosity

The tension that equates to the proper definition of macroporosity (60-75µm) is roughly 4-5 kPa, which I was not able to measure reliably using my WR apparatus. Therefore, I have used 10 kPa (equivalent pore diameter= 30µm) as an approximation of macropore volume.

The approximated macropore volume of a sample is calculated as the difference between its VWCs at saturation and 10 kPa, as shown in **Error! Not a valid bookmark self-reference.**:

Equation 7 $$\boldsymbol{\theta_{>30\mu m} = VWC_{0kPa} - VWC_{10kPa}}$$

Effective Porosity

In order to compare my results against Ahuja et al.'s predicted relationship between Ksat and effective porosity ($\theta_{effective}$), I had to calculate the difference in water retained between saturation and 33 kPa (Equation 8).

Equation 8 $$\boldsymbol{\theta_{effective} = VWC_{0kPa} - VWC_{33kPa}}$$

Water-filled porosity curves

I have attempted to normalize the WR results for packing differences by converting the VWC results for each sample at each tension to an equivalent water-filled porosity (WFP), which is the percent of each sample's pore volume that contains water at a given tension (Equation 9).

Equation 9 $$\boldsymbol{WFP = \frac{VWC}{\theta_{Total}} \cdot 100\%}$$

Pore volume drained freely by gravity

I also tested the WR properties of Soil M in the finished Ksat columns by allowing them to drain freely by gravity (e.g. Laird et al., 2010). These tubes were amended at the same nominal BC rates as the WR rings and were packed similarly. This was done after the 1st, 2nd, and 6th Ksat runs. Once the Ksat experiment was concluded the water head of each column was drained off using a syringe and the column's saturated weight was measured. Columns were replaced on top of their funnels and covered with Parafilm to prevent evaporation. After 48-51 hours of free gravitational drainage, the columns were weighed again to determine their freely-drained water content. Dry soil weight and bulk density were then determined by oven-drying entire tube contents, allowing GWC and VWC calculations based on tube weights.

The pore volume that is drained freely by gravity (θ_{grav}) from a tube is calculated as the difference between its VWCs at saturation (post- Ksat run) and after 48 hours of free drainage (Equation 10).

Equation 10 $$\boldsymbol{\theta_{grav} = VWC_{saturated} - VWC_{drained}}$$

Gravimetric Water Content (GWC)

Gravimetric water was calculated with the equations below (Equation 11-13):

Equation 11 $$\boldsymbol{GWC = \frac{M_{Water}}{M_{ds}}}$$

where M_{ds} is the mass of dry soil in a ring determined by post-experiment oven-drying (for WR cores and gravity-drained Ksat tubes (runs 1, 2, and 6)) or by oven-dried post-packing subsamples (for Ksat runs 3, 4, and 5). Calculation of GWC from ring or tube weights is shown below (Equation 12 &Equation 13):

Equation 12 $$\boldsymbol{GWC = \frac{M_{Water}}{M_{ds}} = \frac{M_{total} - M_{ring} - M_{Wring} - M_{ds}}{M_{ds}}}$$

Equation 13 $$\boldsymbol{M_{Wring} = M_{w\ blank} \cdot \frac{M_{cloth\ ring}}{M_{cloth\ blank}}}$$

where M_{total} is the measured mass of the soil and ring assembly at a given tension; M_{ring} is the pre-experiment mass of the clean assembly of ring, elastics, and cloth (determined for each assembly); and M_{Wring} (calculated only for WR cores) is the mass of water adsorbed to the soil-free blank ring (weighted by each ring's cloth size, as shown in Equation 13, following the assumption that the cotton cloth holds the vast majority of adsorbed water(Klute, 1986)).

Volumetric Water Content (VWC)

Volumetric water at each tension was calculated with the equation derived below (Equation 14):

$$VWC = \frac{V_{Water}}{V_{Total}} = \frac{\left(\frac{M_w}{\rho_W}\right)}{\left(\frac{M_{ds}}{\rho_b}\right)} = \left(\frac{M_W}{M_{ds}}\right) \cdot \frac{\rho_b}{\rho_W} = GWC \cdot \frac{\rho_b}{1}$$

Equation 14 $$\boldsymbol{VWC = GWC \cdot \rho_b}$$

where ρ_b is the soil bulk density, as determined below; and ρ_W is the density of water, which is approximated at 1000 kg/m^3.

Bulk Density

Equation 15 $$\boldsymbol{\rho_b = \frac{M_{ds}}{V_T}}$$

where V_T is calculated with a cylindrical geometry ($V_T = \pi r^2 h_{ring}$) for Ksat tubes, which requires adjustment for shrinking and swelling in the WR rings:

$$V_T = V_{ring} + V_{swell} = V_{ring} + (V_{cyl} + V_{cap}) \rightarrow$$

Equation 16 $$\boldsymbol{V_T = \pi r^2 h_{ring} + \pi r^2 h_{cyl} + \frac{1}{6}\pi h_{cap} \cdot (3r^2 + {h_{cap}}^2)}$$

where h_{swell} is the measured height above the ring top of the soil column after swelling and is equal to $h_{cap} + h_{cyl}$, and h_{cap} is the height of the swelled portion that is described by a spherical cap geometry; and h_{cyl} is the height of the swelled portion that is described with a cylindrical geometry. For Soil O, $h_{cyl} = 0.7 h_{swell}$ in accordance with observations. For Soil M, $h_{cyl} = 0$ in accordance with observations.

Total Porosity

The proportion of a soil's volume that consists of pore space can be calculated using

Equation **17**.

$$\theta = \frac{V_{pore}}{V_T} = \frac{V_T - V_{soil}}{V_T} = \frac{\left(\frac{M_s}{\rho_b}\right) - \left(\frac{M_s}{\rho_p}\right)}{\left(\frac{M_s}{\rho_b}\right)} = \frac{\left(\frac{1}{\rho_b}\right) - \left(\frac{1}{\rho_p}\right)}{\left(\frac{1}{\rho_b}\right)} = \frac{\rho_b}{\rho_b} - \frac{\rho_b}{\rho_p} = 1 - \frac{\rho_b}{\rho_p}$$

Equation 17 $$\theta = 1 - \frac{\rho_b}{\rho_p}$$

True application rate

The actual BC application rate of each sample tube or ring was calculated based on its properties at the experiment commencement (Ksat tubes) or conclusion (WR rings) using Equation 18, which is derived in Appendix C:

Equation 18 $$\left(\frac{M_{BC}}{Area}\right)_{actual} = \frac{M_{BC\ actual}}{M_{soil\ actual}} \cdot \rho_{b\ actual} \cdot d$$

where *d* is the depth of biochar incorporation.

Saturated Hydraulic Conductivity (Ksat) Experiments

Ksat tests were performed in repacked columns with a constant head method based on Klute and Dirksen (1986). Soil M was tested with the same 0, 10 (5.1), 50 (25.6), and 100T/ha (51.3 g BC/kg soil) treatments [5] as used in the WR study (*n*=6). Air-dry soil and BC were mixed to the correct proportions and then packed into the columns using a carefully-replicated procedure. Soil was added to columns in 4 approximately equal increments, which were methodically packed with a 0.75 cm-diameter metal rod (20 pokes around the perimeter, 10 pokes in the central area), before the top of each layer was lightly scarified to eliminate hydraulic discontinuities. This packing procedure was designed to prevent preferential flow paths and was not concerned with achieving a particular bulk density or porosity. Instead equal force was used to pack each treatment, which allowed each mix to settle to its own bulk density.

[5] Soil M Ksat treatments 0, 10, 50, and 100T/ha will be referred to as MK0, MK10, MK50, and MK100, respectively.

Figure 2. Ksat experimental apparatus showing two pairs of PVC tubes, each pair fed by a hose from a tap and draining into the sink.

In each replication, four 10 cm-diameter PVC columns standing in glass funnels were arranged in pairs of one tall and one short column, which allowed for the water of one column to drain into the other (Figure 2). Treatment-column pairings were varied so that every treatment was in short and tall columns three times each out of the six runs. The bottoms of the PVC tubes were covered by a synthetic mesh with 0.5-mm openings. All columns had approximately equal soil column heights around 15 cm. Tall columns had water heads of 11-13 cm, while short columns had heads of 6-9 cm. After columns were packed, they were saturated gradually from the bottom with tap water inside a large bucket. To minimize entrapment of air, saturation was done in stages over 3-4 days. In the first 4-6 hours, water height was kept at ~2 cm, allowing capillary flow to wet the cores. Then water level was increased in steps over 24-48 hours to become level with the soil surfaces. The submerged soils were then left for 48 hours to fully saturate. Upon saturation, tubes were transferred to the funnel rack for commencement of testing. Testing was performed over 5 to 8 days with each set of replicates. Leachate from each column was collected in a volumetric flask over time periods ranging from 12 to 158 minutes (typically ~30 minutes).

Calculations

Saturated hydraulic conductivity

Ksat was calculated with Equation 19, based on Darcy's Law (Equation 3), where, in this case, $\Delta\Psi$ is the height of the water column measured from the base of the soil column.

Equation 19 $$Ksat = \frac{Q \cdot L}{t \cdot \Delta\Psi \cdot A}$$

Statistical Analysis

Statistical significance has been assessed to a 95% confidence level ($P < 0.05$) using the unequal variance t-test (Ruxton, 2006). This has been performed using Microsoft Excel 2007 software. Manual calculation of t-tests for the Ksat dataset was done to confirm the validity of the program's results (Appendix E).

T-test outputs from Excel are in the form of P-values, which represent the probability of rejecting the null hypothesis when it is actually true (Bluman, 2007). In my analyses, the null hypothesis is that there is NSD between the two treatment means being tested. Therefore, a P-value of 0.05 means that there is 95% confidence that a difference exists between two means.

Calculations

Standard deviation and standard error of samples are calculated as shown in Appendix E. Estimated minimum number of replicates has been calculated using Cohen's (1988) statistical power analysis tables based on a desired confidence level of 95% ($P=0.05$) (Appendix E).

Part 4: Results & Discussion of Soil and Biochar Analyses

Soil Texture and Organic Matter Content

Results

The results for both soil texture and OM content in the <2 mm fractions of both soils are shown in Table 2. Soil O has almost four times as much OM, twice as much silt, and nearly triple as much clay as Soil M. The variance in data was much higher for Soil O. The mineral fraction of Soil O is classified as a sandy loam, and Soil M is a loamy sand.

	% of total soil	% of mineral fraction						
	OM	Sand	CV (%)	Silt	CV	Clay	CV	Classification
Soil O	17.1	56.7	14.9	31.0	14.2	12.2	33.2	Sandy loam
Soil M	4.0	78.1	0.1	17.5	0.8	4.4	4.8	Loamy sand

Table 2. Gravimetric results of OM and soil texture tests for the <2mm fractions and resultant classification according to the Canadian System of Soil Classification.

The particle size distribution of soil M as it was used for the Ksat columns (i.e. sieved to 5mm not 2mm) is shown in Figure 3. With this sieving 82% of Soil M by weight is sand-sized or larger. Sand less than 1 mm in diameter is the dominant particle size, and there is prominent fine gravel content.

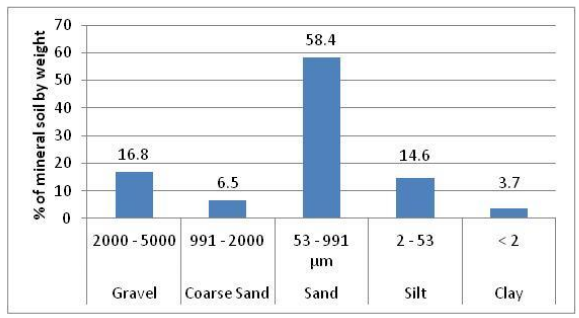


Figure 3. Particle size distribution of Soil M used in the Ksat tubes. OM weight (~4% of mineral weight) has been excluded.

Discussion

The analysis of these two soils was a very good illustration of the differences in soil properties that can occur within a short distance. The reddish-brown, sandy loam Soil O fits the characteristics described in soil surveys for the Bhf horizon of Quimper soil association component 'QP3', a Ferro-Humic Podzol (FHP) that is situated in edaphically wetter areas (Chatterton et al., 1981; Jungen, 1986). Vancouver Island FHPs are known to exhibit two maxima of OM content in their diagnostic Bhf horizons, with the upper one occurring at ~10cm depth (Sanborn and Lavkulich, 1989a). The mean OM content of a Bhf horizon is just over 10% (Carter et al., 1985), but may range as high as 24% at depths of 10-20 cm (Sanborn and Lavkulich, 1989a). Soil O, with 17% OM content (approximately 10% C content), fits within this range, and is classified as Bhf soil horizon because its C content is greater than 5% (NRC, 1998).

The high OM content of FHPs is related to topographical and textural drainage properties. Topography exacerbates soil wetness, which drives illuviation of OM to less biologically-active depths, and inhibition of decomposition may occur from soil wetness (Carter et al., 1985; Schaetzl and Anderson, 2005). The tendency towards finer texture of FHPs like Soil O (relative to other Podzols) facilitates the accumulation of OM through increased surface area interactions (Sanborn and Lavkulich, 1989b). Soil wetness is in turn increased by higher OM contents and textural properties (Carter et al., 1985). The zones in FHPs with the highest OM tend to be influenced heavily by root decomposition and subsequent iron accumulation (Sanborn and Lavkulich, 1989b), which seems to explain both the high OM concentration and the reddish-brown colour of this soil.

The dominant soils of the Quimper soil association are Humo-Ferric Podzols, of a gravelly loamy sand texture, which matches the fine fraction of Soil M. The 'gravelly' textural modifier is assigned to soil with greater than 35% gravel content (2-75 mm-diameter) (NRC, 1998). If I had weighed the boulders I left in the field and the >5 mm fraction that I sieved out, I am sure I could confirm this designation. Soil M lacked the high OM content of Soil O, owing to its better drainage characteristics.

I am not sure how much, or any, of the high variation in soil texture results from Soil O can be attributed to the method I chose to employ. Bohn and Gebhart (1989) have criticized the use of 2-hour sedimentation periods to separate silt and clay for being unreliable, especially as OM increases. The rapid method of textural analysis omits chemical pre-treatment of soil to remove OM in order to expedite and simplify the procedure (Kettler et al., 1999). This was proven to be an acceptable simplification in soils with OM contents below than 3%, but the authors did not address high OM soils like Soil O (Kettler et al., 1999). Therefore, I have more confidence in my results for Soil M than Soil O, which is supported by their respective variances (Table 2). I would have greater certainty as to whether the variance was real or experimentally-induced if I had dry-ashed subsamples from each Soil O replicate, which would have avoided the assumption that the two replicates' OM contents were equal for each size class fraction. Also, using entire samples of the sand, silt, and clay fractions rather than subsamples would improve certainty in my method's results.

Biochar Particle Size Analysis

Results

Dry sieving of BC (n=1) indicated that the BC I used was dominated by sand-sized particles (> 90% by weight) (Table 3). In particular, sand-size d particles less than 1 mm in diameter seemed to be dominant. More than seven percent of the Ksat BC was larger than 2 mm in diameter (Table 3).

	% of biochar weight	
Size class (µm)	WR sieving (2 mm)	Ksat sieving (5 mm)
> 2000	-	7.3
991 - 2000	18.2	16.9
425 - 991	35.3	32.8
105 - 425	33.2	30.7
53 - 105	4.9	4.5
< 53	8.4	7.7

Table 3. The sieved BC sample was dominated by sand-sized particles, particularly sand-sized particles less than 1mm in diameter. There was a sizeable coarse (> 2 mm) fraction in the Ksat BC.

Discussion

My results were affected by loss of dust during transfers of BC**,** adherence of dust to sieves causing over-estimation of sand-sized particles, and possible selection biases in the sample of BC I used (i.e. size sorting within the bin). I estimate that the former two sources of error would not account for more than 2 grams of BC (less than 2% of the 133.15 g sieved). I was careful to minimize effects of size-sorting within my BC container by sub-sampling from various depths and locations, however, I cannot speak to any possible size-sorting within the larger drum used for field applications. There is also the question of how much BC was not sieved adequately within 65 minutes and thus was counted as coarser particles, even though everything did appear to me to be properly sieved.

Despite the above uncertainties, I am confident that my results in Table 3 are accurate to within 5% in describing the particle size of the few litres of BC I used for my experiments. The fine sand-dominated nature of this BC indicated by these measurements is accordant with my observations.

Biochar Particle Density

Results

The mean particle density of our BC was found to be 1270 $\pm$ 54 kg/m^3 (95% confidence interval) with relatively low variation between the 4 replicates (CV = 2 .7%).

Discussion

The particle density of our Douglas-fir BC (pyrolized at 400 - 420°C) is similar to the commonly accepted bulk density of OM (1300 kg/m^3) (Brady and Weil, 2007), and compares well with other results for conifer BC. Monterey pine (*Pinus radiata*) BC produced at 350°C and 500°C had particle densities of

1090 and 1600 kg/m^3, respectively, measured with a water pycnometer (Taghizadeh-Toosi et al., 2011). Assuming a linear relationship (which is a gross simplification (Brown et al., 2006)), the interpolated value from their data for a pyrolysis temperature of 410°C is 1290 kg/m^3, which is very near to my estimate. Pitch pine (*Pinus rigida*) BC produced at 450°C has shown particle densities between 1360 and 1390 kg/m^3 using helium pycnometry (Brown et al., 2006).

It may not be accurate to compare my particle density data with research papers that use the standard helium pycnometry method. It is well-known that different pycnometer media give different density results (Lowry, 1924). To know the absolute density of a material, helium gas is preferred because it is inert and will fill essentially all pore space, whereas water is a larger, polar molecule that behaves as a capillary liquid and may not fill all pore space, especially if the BC exhibits any hydrophobicity (Smith and Howard, 1942). Therefore, it seems appropriate that my calculations of BC particle density are slightly lower than Brown et al.'s (2006) results using helium pycnometry.

Since I am studying soil-water interactions it may be preferable that I have used water pycnometry, even if it may cause underestimation of true particle density. Pores that did not adsorb water during the testing will be counted as solid volume in my calculations, which is essentially how they are behaving. Although this is conceptually similar to the idea of effective porosity in fluid conductivity studies (Ahuja et al., 1984, 1989; Koponen et al., 1997), the pore volume described by effective porosity is not the same as the pore volume that I have excluded here. The threshold soil water potential for effective porosity is 33kPa (equivalent pore diameter = 10 µm), which is quite large in terms of BC porosity, much of which lies in pores smaller than 1µm (Yu et al., 2006; Downie et al., 2009), and is many orders of magnitude larger than pores that might not readily take up water (Kinney et al., 2012).

Part 5: Results & Discussion of Water Retention Tests

Packing of WR Cores

Results

	Mean ρ_b	CV (%)	Mean θ	CV (%)	Mean T/ha	CV (%)
0T/ha	1028.5	2.0	0.543	1.7	0.00	-
5T/ha	1043.9	1.6	0.536	1.4	4.76	1.6
10T/ha	1018.7	2.3	0.546	1.9	9.32	2.3
50T/ha	980.6	1.6	0.560	1.3	45.97	1.6
All samples:			0.546	2.2		

Table 4. Soil O Bulk density (kg/m3), porosity (m3/m3), and true application rates (T/ha) of Soil O WR cores at the experiment conclusion.

	Mean ρ_b	CV (%)	Mean θ	CV (%)	Mean T/ha	CV (%)
0T/ha	1490.2	1.7	0.414	2.3	0.00	-
10T/ha	1470.3	2.5	0.420	3.4	11.61	2.4
50T/ha	1324.3	1.3	0.473	1.5	50.89	1.2
100T/ha	1264.7	1.2	0.490	1.2	95.63	1.2
All samples (n=20):			0.449	7.7		

Table 5. Soil M Bulk density (kg/m3), porosity (m3/m3), and true application rates (T/ha) of Soil M WR cores at the experiment conclusion..

The statistics describing the final packing of the WR cores are presented in Table 4 and Table 5. Full summaries of properties as they varied during the experiment are in Appendix F. Swelling after saturation caused significant changes to core bulk densities and porosities. Soil O cores swelled 9.4% in volume on average, while Soil M cores initially swelled 8.9% then shrunk back to only 1.5% extra. The amount of swelling was larger with increasing BC content for both soils, and the amount of shrinking in Soil M was smaller with increasing BC content (Appendix F). Relative to their respective controls, BC caused less distinct changes to the porosity and bulk density of amended Soil M cores than it did to their Soil O counterparts. Because all samples did not match their target bulk densities, true application rates of Soil O were 0, 4.8, 9.4, and 46.0 T/ha and rates of Soil M were 0, 11.6, 50.9, and 95.6 T/ha (Table 4 and Table 5).

Discussion

Both soils fit expected field bulk density ranges for CR soils (Drewitt et al., 2002). However, Soil O matched the bulk density reported for the topsoil (< 10 cm) rather than its actual 10 - 20 cm sampling depth. This seems to have been related to its high OM content.

My packing goal was for Soil O and Soil M to have equal porosities in all treatments. This proved not to be possible due to swelling of cores at saturation. All treatments of Soil O swelled to a porosity that was not matched by any Soil M treatment (Table 4 and Table 5). Despite the greater swelling in Soil O, it showed much less variation in porosity across treatments than Soil M. This was because M0 and M10 treatments settled at bulk densities beyond 1450 kg/m^3, giving porosities in the neighbourhood of

0.42 m^3/m^3, which could not be matched with the M50 and M100 treatments using my vise apparatus. Therefore, I had to give up on the ideal of equal porosities and accept that the each treatment was going to express its own 'characteristic porosity'. Later I had to follow the same principle in Ksat tube packing, where the similarity between the initial porosities of Soil M in the Ksat tubes and the WR rings, despite their different packing methods, reinforce the idea of characteristic porosity. I do not think that the difference in porosities between treatments diminishes the quality of my results because it is an accurate reflection of each mix's properties, not an arbitrary decision or the product of experimental error.

Although miscalculations and swelling-shrinking caused true application rates to be unequal from the planned application rates, for simplicity I will continue to refer to them with their nominal application rates. This is not unlike field experiments where bulk density is averaged over a wide area and BC is applied evenly to the treatment area in spite of soil variation.

Water Retention Curves

Results

The water retention curves of both soils are plotted together in Figure 4. Every treatment of Soil O retained significantly more water ($P<0.001$) than all treatments of Soil M at all tensions, with the difference between the soils increasing with tension. Mean VWC for each treatment of each soil at each tension is presented in Appendix J.

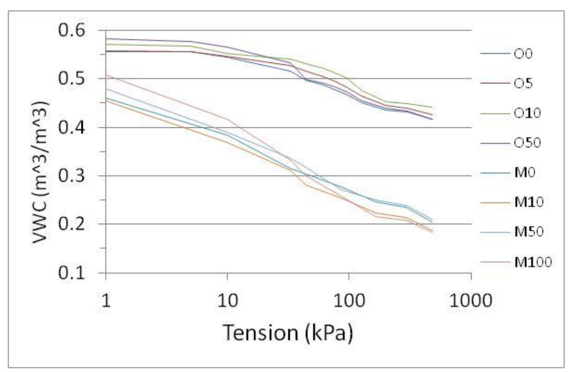


Figure 4. The WR curves of both soils plotted together show the potential for vast differences in soil properties within a site, and the comparatively small changes to WR that come from BC amendment of two relatively coarse soils.

Soil O

Soil O's WR curve (Figure 5) shows that BC-amended treatments had higher mean VWCs than the control soil at almost all tensions, but these differences were usually not significant, as highlighted in Table 6. O5 did not increase VWC over the control at any tension, but improvements over the

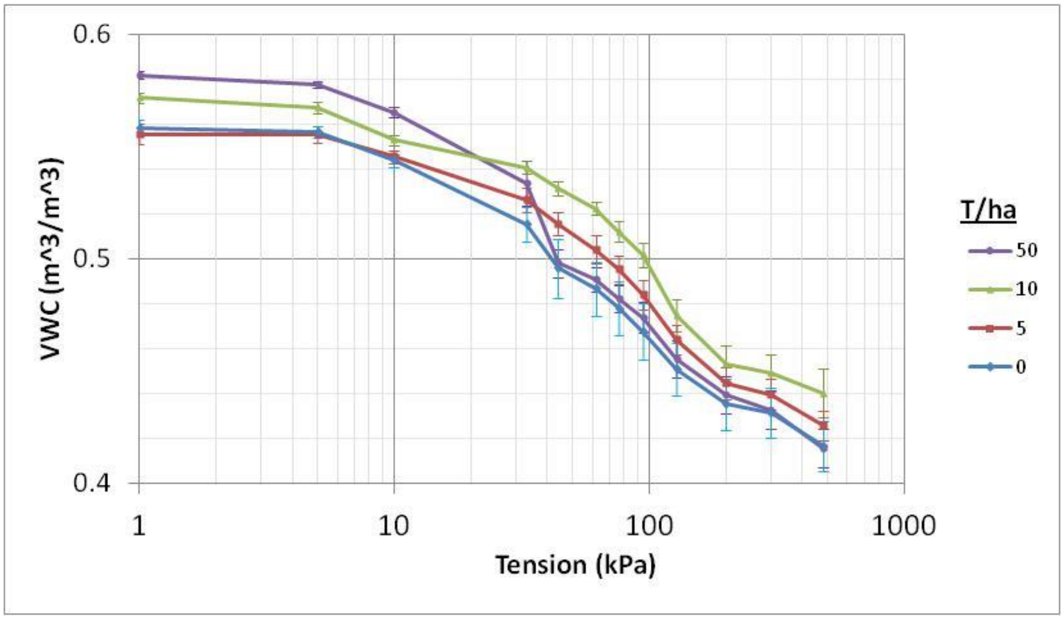


Figure 5. Soil O's WR curve showing losses in volumetric water as tension is increased.

Treatments Compared (T/ha)		Tension (kPa)											
		0	5	10	33	44	62	76	95	128	200	300	483
		P-values from two-tailed, unequal variance t-tests											
0	5	0.779	0.796	0.594	0.270	0.207	0.229	0.228	0.273	0.350	0.484	0.542	0.473
0	10	0.103	0.006	0.018	0.029	0.049	0.039	0.041	0.050	0.138	0.233	0.255	0.181
0	50	0.018	0.0001	0.0002	0.212	0.885	0.767	0.759	0.681	0.779	0.777	0.933	0.957
5	10	0.048	0.007	0.031	0.030	0.017	0.012	0.045	0.051	0.294	0.417	0.402	0.318
5	50	0.008	0.0001	0.0002	0.554	0.065	0.120	0.150	0.300	0.425	0.650	0.554	0.375
10	50	0.133	0.005	0.003	0.541	0.005	0.004	0.009	0.022	0.144	0.296	0.244	0.144

Table 6. Soil O. P-values from two-tailed, unequal variance t-tests of differences between mean treatment VWCs at each tension. Highlighting is colour-coded to separate 99.9% (blue), 99% (green), 95% (red), and 90% (grey) levels of confidence that the treatments being compared are significantly different.

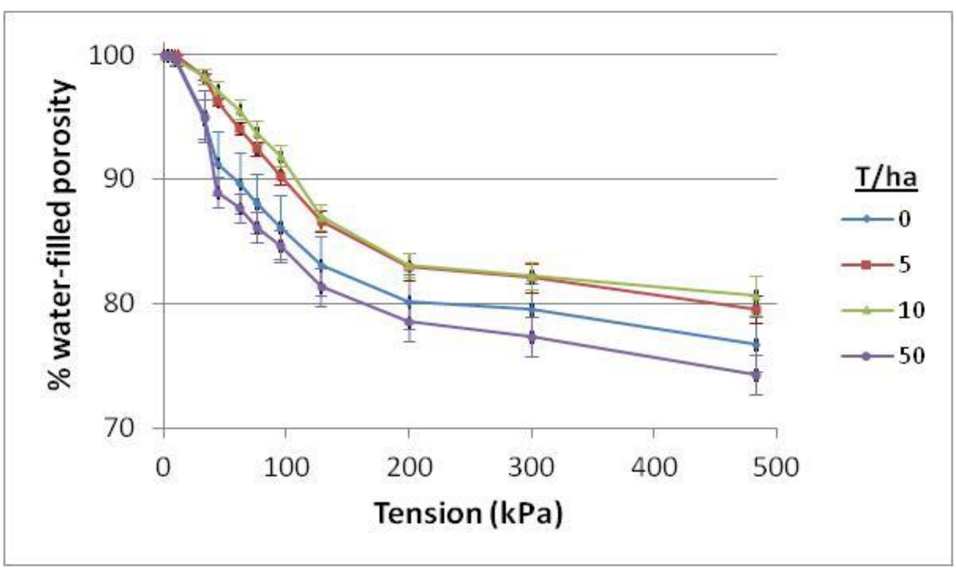


Figure 6. Soil O's WR results expressed as water-filled porosity ($\frac{VWC}{\theta_{Total}}$). By their % drainage between 0 kPa and 44 kPa O0 and especially O50 show that they had a higher proportion of macropores in their total porosity than O5 and O10, leading to O50 showing significantly lower WFP (P<0.05) at all tensions higher than 44kPa, and the highest AWC of all treatments.

control were significant (P<0.05) for O10 at tensions between 5 and 95kPa, and for O50 only from saturation to 10kPa. At FC (33kPa) O10 held significantly more water than O0 (+4.9%) and O5 (+2.8%) (P<0.05). No significant differences exist between any treatments beyond 95kPa.

Significant differences that exist between the VWCs of O5 and O10 between saturation and 76 kPa (and the vast OM and textural differences between the two soils), prove the mistake I made by not keeping the more practical 5 T/ha treatment for my test with Soil M (Appendix D).

Soil O results normalized for porosity differences using WFP curves (Figure 6) show that O50 seems to have lost more of its pore volume in the low tension range (<44 kPa) than the other two BC amendment rates, but then behaved similarly thereafter. This led to significantly lower WFP in O50 compared to the two lower treatments (05 and O10) at most measurements beyond 44 kPa (P<0.05, Appendix G). O5 and O10 show *higher* WFP than the control at all tensions (some differences significant at P<0.10, Appendix G). On the contrary, O50 shows *lower* WFP than the control at all tensions past 33kPa (some differences significant at P<0.10, Appendix G).

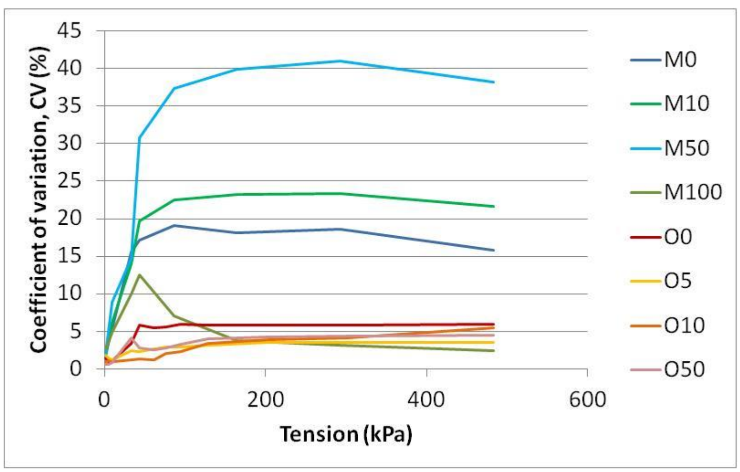


Figure 7. Variation in mean VWCs of each treatment over the range of tensions tested (not plotted logarithmically). M50, M10, and M0 have much higher CVs than the five other treatments, including the highest treatment of Soil M (M100).

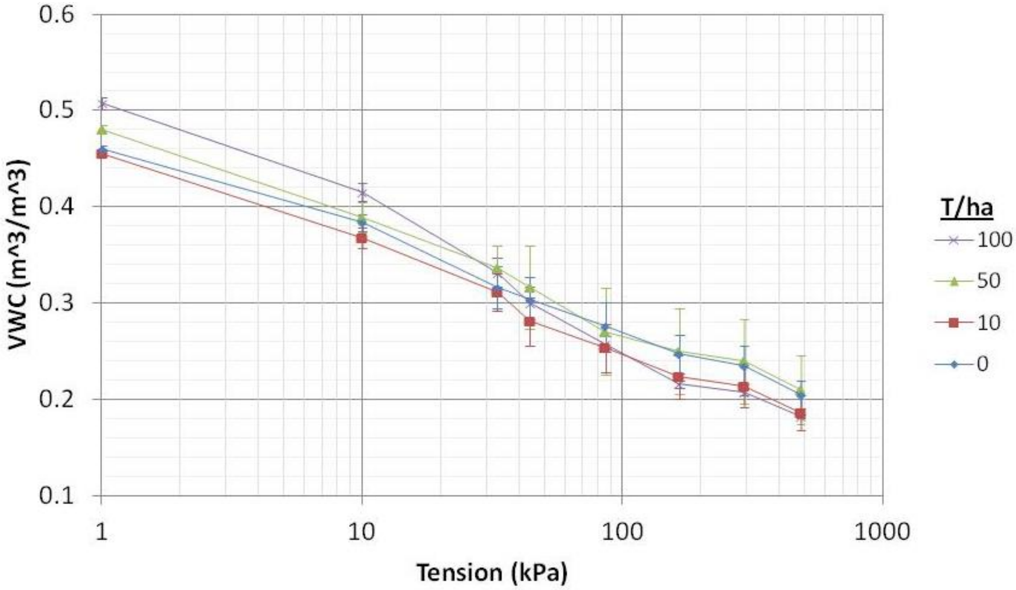


Figure 8. Soil M's WR curve showing VWC (m^3/m^3) losses with increasing tension (kPa) from saturation to 483 kPa.

Treatments Compared (T/ha)		Tension (kPa)							
		Saturated	10kPa	33kPa	44kPa	86kPa	165kPa	293kPa	483kPa
		P-values from two-tailed, unequal variance t-tests							
0	10	0.4088	0.2813	0.8850	0.5140	0.5171	0.4751	0.4859	0.4508
0	50	0.0109	0.7668	0.5200	0.8102	0.9020	0.9601	0.9352	0.9010
0	100	0.0003	0.0379	0.5697	0.8909	0.4741	0.1945	0.2234	0.1996
10	50	0.0027	0.2853	0.4155	0.5026	0.7529	0.6285	0.6193	0.5817
10	100	0.0002	0.0083	0.4360	0.5427	0.8817	0.7402	0.7849	0.8408
50	100	0.0077	0.1884	0.8517	0.7382	0.7924	0.4894	0.5025	0.4900

Table 7. Soil M. P-values from two-tailed, unequal variance t-tests of differences between mean treatment VWCs at each tension. Highlighting is colour-coded to separate 99.9% (blue), 99% (green), 95% (red), and 90% (grey) levels of confidence that the treatments being compared are significantly different.

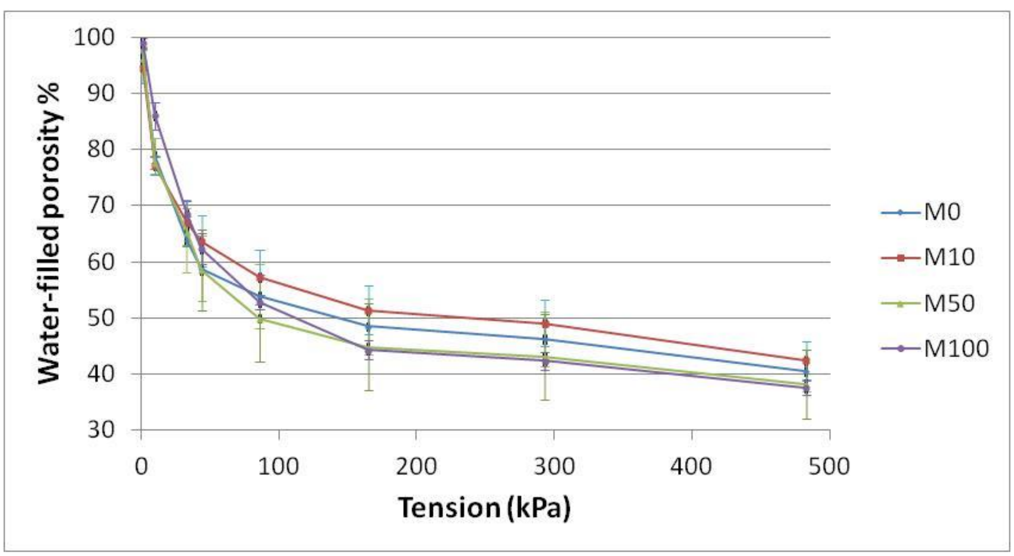


Figure 9. Soil M's WR results expressed as water-filled porosity ($\frac{VWC}{\theta_{Total}}$). There are no significant differences between the two soils, except between M10 and M100 at 10kPa.

Soil M

Soil M (Figure 8) had a much different WR curve than Soil O. Only at saturation and FC (10kPa) did BC-amended soils show significantly higher ($P<0.05$) VWCs than the control soil (Table 7). M10 actually had the lowest mean VWC at all tensions up to 86kPa, but this difference was not significant past 10kPa ($P=0.05$) (Table 7). At tensions higher than 10kPa there are no significant differences in VWC between any treatments owing to high variation in data. The average CV of the four treatments is over 20% at tensions beyond 44kPa, and especially high in M50 data (Figure 7). Figure 7 also shows that variation was much higher in Soil M than in Soil O, which can probably be attributed to packing difficulties in the coarser soil (see AWC Discussion).

There was only one significant difference between treatments in the WFP data (O10 > O100 at 10 kPa, $P < 0.05$). All treatments lost water at a similar rate on the WFP curves (Figure 9).

Discussion

Soil O was able to retain higher amounts of water with or without BC owing to its higher porosity (and higher apparent microporosity), higher silt and clay contents, and higher OM content. Figure 4 effectively demonstrates the scale of WR improvements that practical rates of BC amendments may be able to provide. My results show that a particular soil may experience significantly higher water retention with BC, but that BC's influence is far less than the influence of inherent differences in soil texture and OM that may occur in soils derived from the same parent material. Figure 10 illustrates the same idea using WFP curves from all treatments.

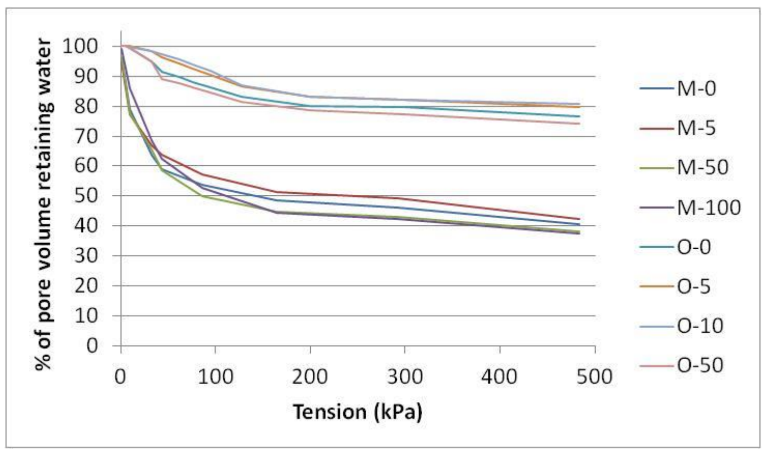


Figure 10. The two water-filled porosity (WFP) curves (not on logarithmic axis) illustrate the strong differences between the two soils, especially in macroporosity differences at the low tension end.

The trend among soils O0, O5, and O10 is for higher WR (expressed as VWC or WFP) with increasing BC content but this trend did not carry over to O50. Although O50 had the highest VWC at saturation, by 483kPa its mean VWC ($0.42m^3/m^3$) was identical to that of the unamended soil. This higher VWC loss was a benefit to O50's AWC (see AWC section below).

The WFP curves of Soil O treatments indicate that O50 had a much higher relative volume of large pores than did the lower BC amendment rates, but not more than the control (Figure 6). If this drained porosity were accounted for by internal BC porosity, we would expect a linear relationship between volume and BC rate (assuming identical BC particle size in all additions). This linear trend is not seen here. On the other hand, the effects of BC amendment rates on densities of macropore packing voids are likely to be non-linear, which may account for the non-linear trend here (Gupta and Larsen, 1972). It makes sense that Soil O would see the larger change in pore size distribution of the two soils because its particle size distribution was changed more strongly (Table 8). At higher tensions, the lack of difference between Soil O treatments fits with Uzoma et al.'s (2011) results that showed almost all WR differences at low tensions (<100 kPa).

	Sand Content (% by weight)		% increase
	Soil Only	Soil + BC	w/ BC
Soil O - WR	56.7	58.4	3.0
Soil M - WR	78.1	78.7	0.8
Soil M - Ksat	81.7	82.3	0.6

Table 8. Changes to sand-sized particle content caused by 50 T/ha of BC are strongest in the finer-textured Soil O.

For the most part, all treatments of Soil M behaved similarly in the pressure plate tests. There were far fewer significant differences in WR between Soil M treatments than there were in Soil O, and none seen beyond FC (10 kPa), expressed as VWC or WFP. The lack of strong differences between Soil M treatments agrees with the results of Gaskin et al.'s (2007) studies in a loamy sand amended with pine chip BC rates up to 88T/ha. Again, the lack of differences at high tensions (> 100 kPa) fit Uzoma et al.'s (2011) results, but the lack of significant data trends among Soil M treatments must also be attributed to the much higher variance in its data (Figure 7). I agree with Streubel et al.'s (2011) assessment of the difficulty of uniformly packing coarse soils and the apparently strong effect that can have on variance in WR results.

The fact that all treatments of Soil M lose water at similar rates on WFP curves (Figure 9) suggests that differences in Soil M's WR with BC amendment occur because of increased porosity in all size classes, rather than from changes to pore size distribution, unlike what was suggested by Soil O's WFP curve. This is supported by the macroporosity results (see below), which showed that all Soil M treatments had similar volumes of large pores.

AWC

Results

Treatment (T/ha)	Mean AWC (m^3/m^3)			
	Soil O (33kPa)		Soil M (10 kPa)	
0	0.099	a	0.179	b
5	0.100	a	-	
10	0.100	a	0.181	b
50	0.118	a	0.179	b*
100	-		0.233	c

Table 9. Comparison of the two soils' AWCs. Letters denote significant differences (P<0.01; the * denotes P<0.10

There are very strong differences in AWC between the two soils. Unamended Soil M provides 81% more AWC than Soil O, as does M10 relative to O10, while M50 provides 53% more AWC than O50 (P<0.001).

In Soil O, there were no significant differences between any two treatments, which collectively show an average AWC of 0.104m^3/m^3 (Table 9). The strongest difference between treatments is an 18.8% increase between O0 and O50 (P=0.16, estimated minimum number of replicates to achieve P=0.05 is16).

In Soil M, the lower rates of BC application (M10 and M50) do not show any significant differences in AWC from each other or the control. However, M100 does show a statistically significant 28-30% increase in AWC over M0 and M10 (P<0.01), and a similar increase over M50 at a lower confidence level (P=0.076, minimum replicates =12).

Discussion

<u>My results indicate that AWC improvement is not likely to be an ancillary benefit of the CR field applications at rates of 5 T/ha.</u>

In both soils, amendment rates of 50T/ha or less caused no significant difference in AWC from the control treatments, and only the 100 T/ha rate in Soil M was significantly different from its control. This shows that it is possible for BC to improve this coarse soil's AWC, but only at very high rates of BC application that are not very practical for field application (Uzoma et al., 2011).

Soil M's highest application rate (M100) showed significant improvements in AWC over the other 3 treatments, at very high application rates. The fact that it took 100T/ha to significantly improve Soil M's AWC while studies with sand have shown significant differences at 10-13 T/ha (Uzoma et al., 2011; Brockhoff et al., 2011) indicates the extremely important contribution to WR and AWC that a relatively small silt and clay fraction in a soil (21.8% in Soil M) can provide.

The differences between the two soils in AWC can be attributed to their differing texture and OM contents. Soil O at this bulk density is simply too strongly dominated by micropores between its fine particles to release water, whereas Soil M releases water easily due to its macropore-dominated structure.

All treatments of Soil O have a very low AWC. Despite the low final bulk densities of all Soil O treatments, the vast proportion (~70% of WFP) of Soil O's stored water would be unavailable to plants at the levels of compaction in my experiment. The low AWC of unamended Soil O in my experiment is almost certainly caused by a lack of macropores in my uniformly packed rings, which is contrary to the high concentrations of roots (alive and dead) found in true Bhf horizons (Sanborn and Lavkulich, 1989a), which I sieved and picked out of my soils.

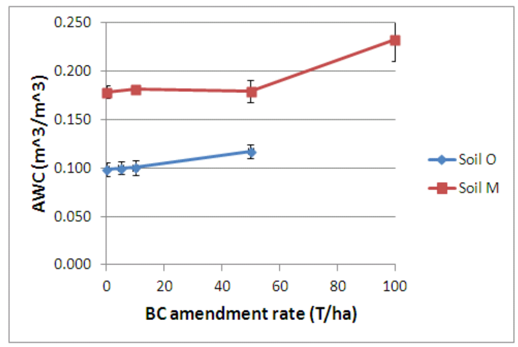


Figure 11. The effect of BC amendment on AWC for both soils. A significant increase in AWC for M100 creates a non-linear pattern in Soil M's data. Error bars = 1 SE

The non-linear trend in Soil M's data between AWC improvements and BC rate (Figure 11) may be related to non-linear effects on soil packing from adding coarse BC to a coarse soil (Gupta and Larsen, 1972). One study that encountered non-linear patterns of WR in BC-amended soil suggested that a soil's threshold to accommodate any hydrophobic materials in BC may be exceeded at high application rates, especially in low-surface area coarse-textured soils, causing WR reduction (Dugan et al., 2010). However, I believe that hydrophobicity is unlikely to be a factor in my results. The fact that our BC caused significant GWC and VWC increases at saturation in both soils, including the high-OM Soil O, indicates strong sorption of water by BC. Furthermore, hydrophilic properties of BC are generally strongest with HTT of 400°C to 500°C (Kinney et al, 2012). Therefore, it seems likely that differences in packing and total porosity were the main contributors to M100's improved AWC.

Macroporosity

Results

There are strong differences between the two soils in their macropore volumes (volume drained at 10 kPa). Unamended Soil M has more than five times the macropore volume of Soil O, and more than six times as much when expressed as a percentage of total pore volume (Table 10). At all shared BC rates the differences between the two soils are similar.

Treatment (T/ha)	Macroporosity (>~30µm-diam.) m^3/m^3		% of total porosity	
	Soil O	Soil M	Soil O	Soil M
0	0.014	0.076	2.6	16.6
5	0.010	-	1.9	
10	0.019	0.087	3.4	18.9
50	0.016	0.091	2.9	18.0
100	-	0.092	-	18.0

Table 10. Treatment mean values for macroporosity, expressed volumetrically and as a percent of total porosity. Soil M is much higher than Soil O for both.

There are no significant differences in macropore volume (**Error! Reference source not found.**) between any treatments of a soil. The strongest difference between Soil M treatments is an apparent 0.016 m^3/m^3 (21%) increase in M100 over the control (P=0.30). The strongest difference in Soil O is the slight 0.009 m^3/m^3 increase in O10 over O5 that actually equates to a near doubling of macroporosity (P=0.23).

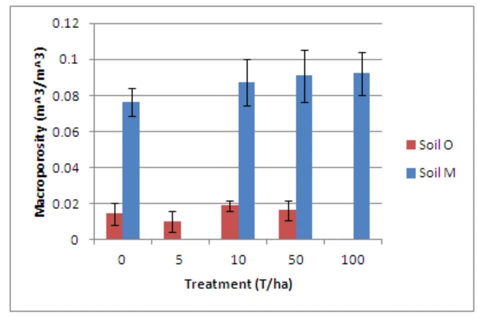


Figure 12. Macroporosity as indicated by volume drained by 10 kPa of tension. Highly significant differences are seen between Soils O and M (P<0.001), but NSD are seen between treatments in either soil.

Discussion

I think that these macroporosity calculations are questionable except for the demonstration of clear differences between the two soils. As expected from its coarse texture and relatively low OM content, Soil M has a much higher macroporosity than Soil O.

The fact that no treatments of a given soil showed significant differences from each other is not surprising because of high variance in the WR data, especially that of Soil M (Figure 7), and uncertainty in my soil volume calculations (Appendix D). Small errors in volume estimations affect macroporosity calculations greatly because the volume drained between saturation and 10kPa is so small (e.g. Soil O ≅ 0.015 m^3/m^3). An average volume calculation error of 1.5% could account for all the 'macroporosity' apparent in my Soil O calculations. Some O10 soils even show slight VWC *increases* between saturation and 10 kPa. Since I have estimated the volume of a lumpy, non-symmetrical swelled soil volume with a simple geometric equation, this is not hard to imagine.

There is a non-significant trend of increased macroporosity in Soil M, which may indicate drainage and aeration benefits from high rates of BC application. However, the results at lower BC rates make it seem unlikely that the CR amendment rates will have measurable impacts on macroporosity, especially when considering the prevalence of macropores in field soils caused by faunal activity and root growth (Carter et al., 1985; Sanborn and Lavkulich, 1989a,b)

Drained porosity at FC

Results

The results for porosity drained at FC are similar to those found for macropore volumes with NSD between treatments, and significant, although less pronounced, differences between the soils at all shared BC rates (P<0.01).

Unamended Soil O has a drained volume of 0.042 m^3/m^3 at 33 kPa which is 44% less than unamended Soil M at 10 kPa (0.076 m^3/m^3) (P<0.05). As a percent of total porosity, Soil O has less than half as much of its pore volume drained at FC than does Soil M (7.8% vs. 16.6%) (P<0.05).

Once again, there is NSD between any two treatments of a given soil. The strongest differences between treatments are seen in Soil O, where drainage effects apparently may not relate linearly to BC rate (Figure 13). The mean volumes drained from treatments O5 and O10 are approximately 30% less than the volumes drained from the control and O100 treatments (P=0.26 to 0.32). Statistical power analysis indicates that more than 35 replicates would be needed to prove significant differences (P=0.05) between members of these two treatment groups. Trends in the results for Soil M are presented above in the macroporosity section.

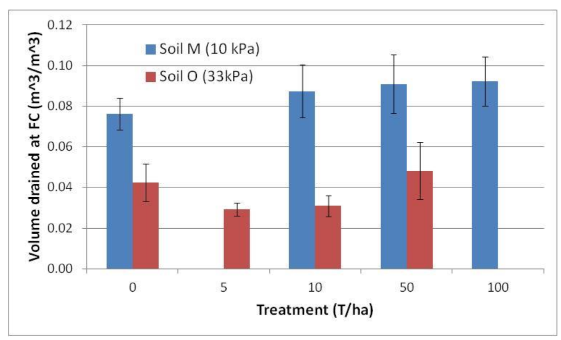


Figure 13. Volume drained at porosity is significantly different between soils at all BC rates, but NSD is seen between treatments of a given soil.

Discussion

The two soils show less difference in their respective VWCs drained at FC than they do in macroporosity calculations because FC has been approximated at 33kPa in Soil O and 10kPa in soil M - thus the same data has been used here for Soil M as was used to calculate macroporosity, while the data for Soil O now encompasses a wider range of tensions. Nevertheless, differences in VWCs drained at FC are again significant between the two soils. Data limitations in regards to soil volume estimation again exist, but are of less relative importance here than the calculations for macroporosity because of the wider range of tensions in this measurement and the resultant higher VWC decrease.

My conclusion from these results is the same as I expressed for macroporosity. Although these results indicate possible differences in the volume drained and aerated at FC in BC-amended soils, in the field I would not expect to find any effect on aeration and drainage from any of my high rates of BC application, let alone from the actual amount applied, because of the prevalence of macropores in field soils (Carter et al., 1985; Sanborn and Lavkulich, 1989a,b).

All of these low tension (< 20 kPa) drainage-related characteristics could be tested more precisely and quickly using hanging water columns (Tuller and Or, 2004).

Gravity-drained porosity

The results presented here are from the tests performed on finished Ksat tubes with nominal BC rates of 0, 10, 50, and 100 T/ha (named MK0, MK10, MK50, and MK100, respectively).

Results

Results of GWC and VWC retained after 48 hours are presented in Figure 14 and **Error! Reference source not found.**. On a gravimetric basis, MK100 retained 40% more water than the control ($P<0.001$), and 33% and 26% more water than MK10 and MK50, respectively ($P<0.05$) (**Error! Reference source not found.**). No other statistically significant differences between treatment means were seen. There was NSD in GWC losses between treatments. On a volumetric basis, differences between treatments were less pronounced. 100T/ha retained 16% more water than the control ($P<0.02$), 14%

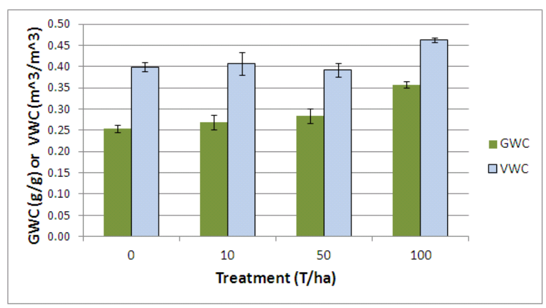


Figure 14. Results from the gravity-drainage experiment done with Ksat tubes filled with soil M (n=3)**.**

Treatment (T/ha)	GWC (g/g) Mean	GWC s	GWC CV (%)	VWC (m^3/m^3) Mean	VWC s	VWC CV (%)
0	0.255 a*	0.015	5.9	0.399 a	0.017	4.3
10	0.269 a	0.029	10.7	0.407 ab	0.046	11.4
50	0.284 a	0.031	10.7	0.392 a	0.027	6.9
100	0.358 b	0.014	4.0	0.463 b	0.009	1.9

Table 11. Gravimetric and volumetric results from the gravity-drainage experiment with Soil M Ksat tubes. *s* is standard deviation. Letters denote statistical significance to P < 0.05, * denotes P = 0.001.

more than 10T/ha (not significant), and 18% more than 50T/ha ($P<0.04$) (**Error! Reference source not found.**).No significant differences were seen between the other three treatments. There was NSD between treatments in VWC losses, which averaged 0.064 m^3/m^3.

Discussion

These tubes had very similar packing characteristics as the WR cores (Table 13). However, there were much larger soil and BC particles in the Ksat tube mix, so macroporosity is likely to have been higher in those tubes, at least initially. By the end of Ksat testing their pore structures are likely to have changed because of soil losses (average of 1.3%) and soil column settling accompanied by presumable filling of macropores.

My results fit variably well with other studies. Novak et al. (2009) found that BC at 40 - 44 T/ha increased gravity-drained water retention by 6.7% - 15.7% (not all significant to $P = 0.05$) on a loamy sand, which is quite similar to MK50, which showed a non-significant 11.6% increase in gravity-drained GWC over the control.

My results from the unamended soil do not make sense with those of Dugan et al.'s (2010) loamy sand which had a GWC below 0.05 m^3/m^3 after overnight gravity-drainage, whereas MK0 had a GWC of 0.255 m^3/m^3 after 2 days. (In fact, their overnight gravity-drained GWC is lower than any of the Soil M WR samples at 483kPa of tension.) This discrepancy may be partially caused by differences in packing (although they have not provided bulk density data for confirmation), but seems likely to be an error on their part. The 10T/ha results were not so strongly different. MK10 had a GWC 28% higher than their 10 T/ha soil (Dugan et al., 2010). Whereas Dugan et al's (2010) results show no further GWC improvement over the control at rates past 5 T/ha, my treatments do not show any significant difference until 100 T/ha.

The statistically equal volume of water lost among all treatments indicates all had similar macroporosity (>60µm, ~5kPa). Although this seems contradictory to the statistically different Ksat results between treatments, it may be that there is an important contribution to Ksat coming from pores too small to drain by gravity.

The VWC measurements from these Ksat tubes can be extrapolated onto the WR curve made with Soil M, where the equivalent tension data fit with Brady and Weil's (2007) estimate of -5 kPa as the equivalent soil water potential of a gravity-drained soil (Appendix H). This gives some support to my use of Soil M WR and Ksat data in combination to compare to Ahuja et al. (1984, 1989) (see Ksat Results).

Part 6: Results & Discussion of Ksat Experiments

Ksat Tube Packing

The physical condition of Ksat soil columns changed between initial packing and the end of the experiment (Table 12) because of illuvial action, both within the soil column causing soil column height reductions and bulk density increases, as well as out of the soil column, causing bulk density decreases. Net increases to the bulk density of columns meant that final actual application rates were 0, 12.1, 55.7, and 102.6 T/ha (0, 5.2, 26.9, and 52.5 g/kg).

T/ha	Mean ρ_b	s	CV %	ρ_b Chg. %	Mean θ	s	CV %	θ Chg. %	Avg T/ha	s	CV %	T/ha Chg. %
0	1576.6	54.4	3.5	2.4	0.405	0.021	5.1	-3.5	0.0	-	-	-
10	1538.7	74.3	4.8	3.1	0.393	0.029	7.4	-4.4	12.1	0.68	5.7	3.1
50	1381.3	58.2	4.2	2.2	0.450	0.023	5.2	-2.4	55.7	3.60	6.5	2.2
100	1303.5	34.4	2.6	0.7	0.474	0.014	2.9	-0.7	102.6	5.32	5.2	0.7
				All samples:	**0.431**	0.039	9.2	-2.8				

Table 12. Soil packing characteristics (bulk density, porosity, and true application rate) of finished Ksat tubes, including percent change from the initial state. All tubes showed a bulk density increase during the experiment and consequent increases in true application rates and decreases in porosity.

Individual tubes lost between 5.3 and 47.3g of dry soil during a run and an average of 1.3% (*n*=12, 3 replicates of 4 treatments, NSD between treatments). The average soil loss is higher (2.5%) when expressed relative to the weight of the size fraction that could actually pass through the 0.5mm mesh, and even higher (5.5%) when accounting for the fact that typically only silt-sized particles and smaller (<0.05 mm) are able to wash through a pore system (Schaetzl & Anderson, 2005).

These problems could have been avoided by using a smaller mesh for column bottoms to reduce soil losses, and by a redesigned apparatus that reduces the water head substantially. My apparatus was designed to allow the top spout pieces to be interchanged between soil column bases to save on scarce materials. In hindsight, this was a foolish shortcut because the resultant columns had unrealistically high water heads. I knew this was mathematically insignificant because of the proportionality of soil and water column heights in Darcy's Law (Equation 19), but failed to account for the effects this could have on the force and turbulence of water flowing through the column, leading to bulk density changes and soil losses.

There is a very strong similarity between the porosities of the Ksat tubes and those of the Soil M WR rings (Table 13; Appendix F). This similarity was stronger for initial Ksat tube packing properties than it was between post-experiment properties, as shown in Table 13.

	Ksat tubes		WR cores	
Treatment (T/ha)	Mean θ	s	Mean θ	s
0	0.405	0.021	0.414	0.010
10	0.393	0.029	0.420	0.014
50	0.450	0.023	0.473	0.007
100	0.474	0.014	0.490	0.006
All samples:	0.431	0.039	0.449	0.035

Table 13. Comparison of porosities of Ksat tubes and WR rings in their post-experiment state.

Ksat Tests

Results

Data for the Ksat experiment had to be treated with regard to the variations in flow seen as the experiments progressed (Appendix I). Generally the pattern was for decreasing flow rates initially followed by steady or increasing flow rates, particularly towards the end of a run. Therefore, only data collected on days 2, 3, and 4 have been used to calculate mean Ksat for each run.

The data from all 6 Ksat runs are shown together in Figure 15. The high variation within treatments from run-to-run stands out, especially in the control soil and MK100. Therefore, the relationship between treatment means in a given run is often different from the MK0≅MK10 < MK50 < MK100 relationship seen in the overall means.

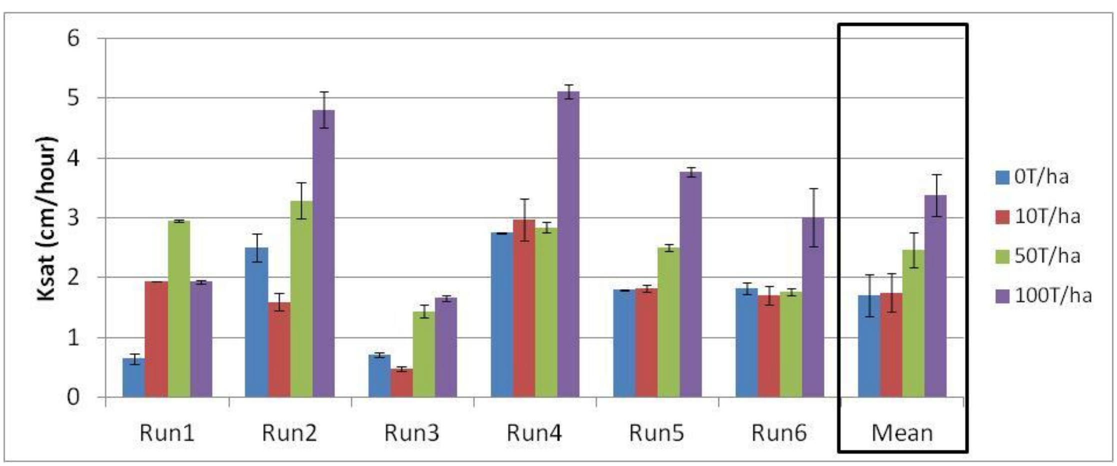


Figure 15. Ksat results for each run and the mean of all runs, with standard error bars. Means and variance are calculated based on Days 2 – 4 only.

Biochar amendments increased Ksat in Soil M at high amendment rates (MK50 and MK100), but have no effect at the lower amendment rate (MK10). The only significant differences ($P<0.05$) seen in the Ksat tests were between MK0 and MK100 (98% increase) and MK10 and MK100 (93% increase) (**Error! Reference source not found.**). The mean Ksat of MK50 is 44% greater than the control soil, but this difference is not significant ($P=0.13$). The estimated number of samples to detect statistically significant ($P=0.05$) differences between treatments are fairly high (>36) for comparisons of MK10 vs. MK50 and of MK50 vs. MK100.

	Ksat (cm/hr)			
	Mean		s	CV %
0T/ha	1.71	a	0.88	51
10T/ha	1.75	a	0.79	45
50T/ha	2.47	ab	0.72	29
100T/ha	3.38	b	1.44	43

Table 14. Results from the Ksat experiment show significant increases at the highest rate but no significant differences at lower rates. Letters signify statistical significance to P=0.05.

There is relatively high variance in the data, with CVs ranging between 29% and 59%, with the highest CV for MK100 (**Error! Reference source not found.**).

Discussion

Ksat tests in coarse soils with BC (Brockhoff et al., 2010; Uzoma, 2011) led me to believe I might see decreased Ksat with BC application, which was the opposite of my results. I believe the reason for the discrepancy between my expectation and my results are the particle size differences between my BC and that used in other studies. Whereas in the other studies BC was “powdery” (Brockhoff et al., 2010) or sieved to 0.18mm (Uzoma et al., 2011), I used a wide range of BC particle sizes, dominated by sand-sized particles (Figure 16). Therefore, these two other studies’ BC applications had the effect of increasing the amount of fine sand, silt, and clay in their respective study soils, whereas mine actually caused the opposite effect, albeit slightly (percent sand by weight increases from 81.7% in MK0 to 82.2% in MK100).

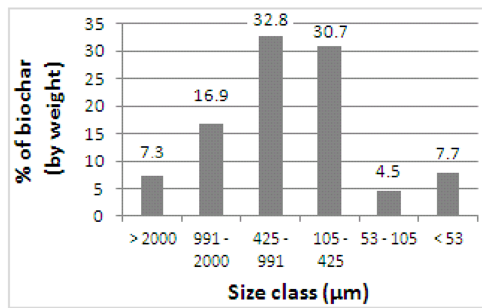


Figure 16. Results of BC particle size analysis performed with dry sieving.

Coarse and sand-sized BC particles should affect the soil macropore structure in a similar way as mineral sands (Downie et al., 2009), meaning that they should increase macroporosity by creating packing voids (Gupta and Larsen, 1972). Increased macroporosity would explain my observed trend of increased Ksat with higher BC rates. The results from Soil M actually resemble the results of studies with

BC amendments to clay and clay loam soils, in which Ksat increases with BC amendment have been linked to increased macroporosity (Asai et al., 2009; Major et al., 2009; Kameyama et al., 2010).

My BC amendments were actually quite similar to those in Busscher et al.'s (2009) study, in which infiltration increased in a loamy sand amended with a coarse (6mm-sieved) BC at rates as low as 6 T/ha (5 g/kg). However, this study tested infiltration into a non-saturated soil to simulate field conditions not saturated flow. Their results at low BC rates suggest that I may have missed possible differences by my selection of rates above 10 T/ha, however, my highly variable results indicate that any such differences would be undetectable.

It needs to be emphasized that my measurements of repacked columns do not represent field soils well. To create uniformity between samples, I carefully packed tubes with the goal of eliminating large macropores (> 2 mm), thus purposely creating experimental conditions that do not match field conditions. Indeed, the CV of my Ksat results is significantly lower than the 75% - 150% CV expected by Pennock, Yates and Braidek (2006) in field soils. The variations in Ksat displayed by individual samples over the course of the experiment can be explained by bulk density changes described above in the packing section.

Through creation of preferential flow patterns, the existence of macropores in the field soil seem likely to obscure the differences in flow rates that I have found to occur through the uniformly-packed portion of the soil profile. Furthermore, my results only show significant differences in Ksat at BC application rates far in excess of the 5 T/ha CR field applications. For both of these reasons, it seems that CR field applications are unlikely to significantly affect saturated water flow through the soil profile. However, it is important to note that these Ksat results do not predict changes to the soil's unsaturated flow regime, which would be common in these well-drained soils, particularly during the growing season.

With the levels of soil loss that I documented, my decision to reuse soil mixes for runs 4 through 6 was not very sound. In fact, three of four treatments did show non-significant 41-65% increases in Ksat between the two data subsets, hinting at a possibly serious source of error.

Effective Porosity vs. Ksat

Results

In accordance with Ahuja et al (1984, 1989) I have graphed my data on two logarithmic axes, one representing Ksat, and one representing effective porosity (the VWC difference between saturation and -33kPa) (Figure 17). My data fits appropriately with the predictions by Ahuja et al. (1989); lower Ksat than predicted for a sandy soil but higher than predicted for loamy soils. There is a considerable degree of variation in my data, as shown by the large standard error bars (Figure 17), which could account for some or all of my data's deviation from the predicted results.

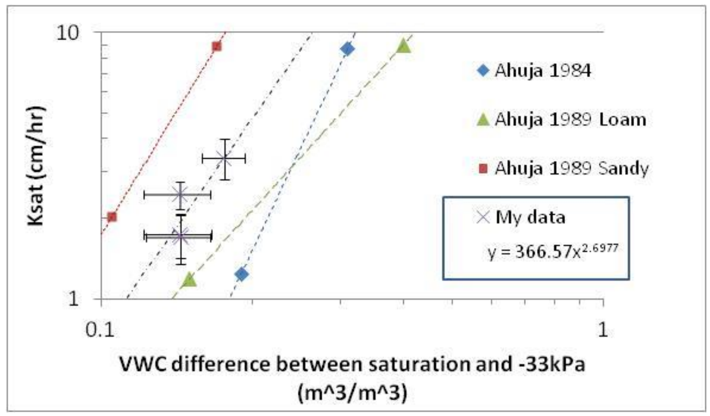


Figure 17. Comparison of the predicted relationships between effective porosity and Ksat with my results. My data lie between the loam curve and the sandy curve, as they would be expected to. The equation at right is for the trendline derived from my results.

Discussion

In my use of Ahuja et al.'s (1984, 1989) relationship, I have made a very big assumption that the soils in the WR cores are similar enough to those in the Ksat tubes to allow their data to be combined. With the soil loss described above, this is a doubtful assumption, even if the two sets of soils did have similar bulk densities and porosities.

On the basis of Poiseuille's Law ($flow\ velocity \propto radius^4$), we should expect Ksat to be higher in soils with greater effective porosity, which is generally the result shown from my tests. The trendline described by my data has a similar slope and shape as the predicted curves from Ahuja et al (1989) (Figure 17). Although Ahuja et al.'s (1984, 1989) relationships would predict Soil M's Ksat to within an order of magnitude (Table 15), it seems that a soil-

		Effective Porosity-based			Texture & porosity- based	
		Ahuja et al., 1984 GENERAL	Ahuja et al., 1989 LOAM	Ahuja et al., 1989 SANDY	Rawls and Brakensiek, 1989	Cronican and Gribb, 2003
Treatment (T/ha)	My data (cm/hr)	Prediction (cm/hr)	Prediction (cm/hr)	Prediction (cm/hr)	Prediction (cm/hr)	Prediction (cm/hr)
0	1.707	0.410	1.090	5.336	808	0.102
10	1.752	0.407	1.086	5.305	-	-
50	2.466	0.402	1.080	5.260	-	-
100	3.383	0.909	1.649	9.865	-	-

Table 15. Comparison of my Ksat data with the three values predicted from my WR core effective porosities using Ahuja et al.'s relationships, and values predicted using two other texture and porosity-based pedotransfer functions.

specific relationship would have to be developed in order to apply their theory to CR soils.

However, their relationship is more accurate than other pedotransfer functions that relate easily-collected physical soil indicators (texture and porosity) to Ksat (Rawls and Brakensiek, 1989; Cronican and Gribb, 2003) (Table 15). I have also compared my data to the relationship predicted by Campbell (1985) for decreasing Ksat with increasing silt and clay content. The MK0 Ksat result is less than half than that expected for its texture (Figure 18).

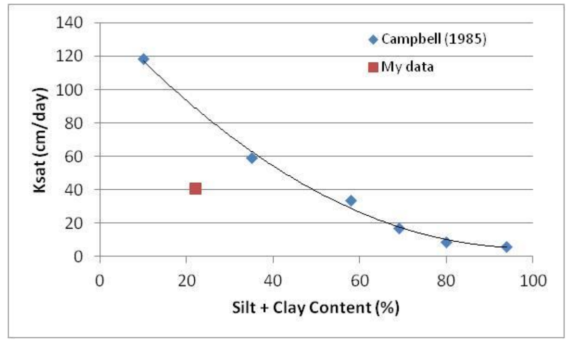


Figure 18. Campbell (1985)'s predicted Ksat for Soil M's texture is more than twice the actual result for the control soil.

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Part 7: Conclusion

In this study, I have examined the changes that BC amendments cause to hydrologic properties of two relatively coarse soils from the CR research site. Improved hydrologic properties would be a welcome secondary benefit of BC applied in this study for soil GHG mitigation, nutrient retention, and C sequestration purposes. My intention was to investigate if benefits of increased water retention and decreased saturated hydraulic conductivity that have been noted in other studies of coarse soils (e.g. (Dugan et al, 2010; Brockhoff et al., 2010; Uzoma et al., 2011) are likely to be realized from the CR BC applications.

My research began with investigation of basic BC and soil physical properties. I found that the particle density of our Douglas fir BC is 1.270 $\pm$ 0.054 g/cm^3 (95% confidence interval), with a particle size distribution dominated by sand-sized particles (Table 3). My two WR study soils were very different from each other in texture and OM, which illustrated site variability very clearly. Soil O was a sandy loam (57% sand/ 31% silt/ 12% clay) with 17% OM, and Soil M was a loamy sand (78%/ 18%/ 4%) with 4% OM (Table 2). I found that BC lowers particle and bulk densities, and increases porosity of soil mixes, and, therefore, a given mix of soil tends to exhibit a 'characteristic porosity' that is not packing-induced. I found it difficult to achieve uniform packing in the coarse-textured Soil M, creating high variance in this soil's WR and Ksat results.

In my WR experiments, the two soils showed statistically significant differences from each other ($P<0.001$) in all WR properties (VWC at all tensions, AWC, macroporosity, and volume drained at FC). These WR differences between soils far exceeded any changes caused to either soil by BC application (Figure 4 and Figure 10). The effects of BC amendments on WR were stronger at low tensions (Soil O < 95kPa; Soil M < 10 kPa), indicating the influence of these BC applications on pore structure and size. In this regard, the particle size distribution of the BC seems to be a strong determinant of its WR effects. However, the changes in porosity induced by BC application, especially increases in macroporosity, seem likely to be small in relation to field variability in these root-rich, biologically-active, coarse-textured soils. My uniformly-packed samples do not represent that natural environment very well, which is a serious shortcoming of laboratory-based soil physics testing, and is reflected in my low confidence of the transferability of my results to field conditions.

There were no differences in AWC over the control for either soil at BC rates of 50 T/ha and less (Table 9), which indicates that the 5 T/ha BC application at CR is unlikely to have any significant effects on AWC, especially in light of the discussion above. At 100 T/ha, Soil M did show significantly increased AWC over the control, which at least demonstrates the possibility for WR benefits from BC in these coarse soils, although at an impractical application rate. My results for volumes drained at 10 kPa (macroporosity) (Table 10), at FC (Figure 13), and by gravity (Table 11) show no significant differences at rates below 100 T/ha, making it seem very unlikely that differences in drainage and aeration will result from low rates of BC application to CR's highly variable soils.

Ksat results from Soil M show significant increases at the highest amendment rate (100 T/ha) over the lower amendment rates, and a possible increase with 50 T/ha, as well (Table 14). However, at 10 T/ha there is no sign of a difference in Ksat over the control, once again making it unlikely that significant differences will occur from CR field applications. Several pedotransfer functions relating Ksat to porosity and/or texture were utilized with my data (Ahuja et al., 1984, 1989; Campbell, 1985; Rawls and Brakensiek, 1989). Although my data was relatively close to their estimates (Table 15), confirming that my Ksat results are reasonable, none of these functions accurately predicted Ksat for soils from my experiment.

In summary, I did not find any strong evidence to suggest that the levels of BC applied in the field at CR will offer benefits for plant-available water holding capacity or aeration and drainage. On the other hand, there was no indication that soil hydrologic properties were negatively affected by BC applications at any rate. This alone is an important result, which was by no means certain beforehand. This knowledge informs assumptions that have been made thus far about our BC's hydrologic properties, and indicates that high BC application rates for other research purposes, particularly C sequestration, can be sustained from the perspective of physical plant-water interactions. The apparent influence of BC particle size on hydrologic effects may be a finding worth pursuing, especially if subsequent tests showed that performance from a GHG and nutrient perspective was not affected negatively by BC particle size.

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Appendix A

Capillary Rise Equation

The height of rise of a column of water is to where upward-acting capillary forces equal the downward-acting forces:

$$\text{upward force}=\text{downward force} \rightarrow$$

$$T \cdot 2\pi r \cdot cos\alpha = d \cdot h \cdot \pi r^2 \cdot g \quad \rightarrow \quad h = \frac{2T \cdot cos\alpha}{r \cdot d \cdot g} \quad \therefore \quad h \propto \frac{cos\alpha}{r}$$

Where: *T*= surface tension of soil solution, *r*=pore radius, *α*=liquid-solid contact angle, *d*=density of soil solution, *h*= height of water column, *g*= gravitational acceleration constant. Surface tension of water and density of soil solution are constants at a given temperature.

h can be converted from cm of water to kPa (1 cm of water = 0.1 kPa)

Conversion of soil wate rpotential (tension) and effective pore diameter

In many instances I have calculated pore diameters from soil water potential (or vice versa). This has been done with an equation derived from data in Brady and Weil (2007).

$$D = 300\,\Psi^{-1}$$

Where *D* is the pore diameter in µm, and Ψ is the soil water potential in –kPa (e.g tension).

Outputs from this equation are shown below:

Soil Water Potential (-kPa)	Pore diameter (µm)
1	300
5	60
10	30
33	9.1
44	6.8
100	3
500	0.6
1500	0.2

Appendix B

The two spreadsheets containing WR and Ksat literature review information are in an Excel file called : litreview.xlsb stored at: _____.

Appendix C

Equal Porosity Packing Calculations

Where: $\theta_0$is the porosity of the unamended control soil at the target bulk density.

$\theta_{mix}$is the porosity of the mix being created

$\rho_{b\ 0}$= $\rho_{b\ TARGET}$ is the target bulk density (1100kg/m^3 for Soil O; 1300kg/m^3 for Soil M.)

$\rho_{p\ 0}$= $\rho_{p\ soil}$ is the particle density of the unamended soil, as determined below.

$\rho_{p\ mix}$is the volume-weighted particle density of the mix being created as determined with the equation derived below.

$\rho_{b\ mix}$is the bulk density that the soil needs to be packed into its rings at in order to achieve the target porosity.

$$\boldsymbol{\theta_0 = \theta_{mix}}$$

$$1 - {}^{\rho_{b\ 0}}/{}_{\rho_{p\ 0}} = 1 - {}^{\rho_{b\ mix}}/{}_{\rho_{p\ mix}}$$

$$1 - {}^{\rho_{b\ TARGET}}/{}_{\rho_{p\ soil}} = 1 - {}^{\rho_{b\ mix}}/{}_{\rho_{p\ mix}}$$

$${}^{\rho_{b\ mix}}/{}_{\rho_{p\ mix}} = 1 - \left(1 - {}^{\rho_{b\ TARGET}}/{}_{\rho_{p\ soil}}\right)$$

$$\rho_{b\ mix} = \rho_{p\ mix} \cdot \left(1 - \left(1 - {}^{\rho_{b\ TARGET}}/{}_{\rho_{p\ soil}}\right)\right)$$

Volume-weighted particle density of soil mixes, $\rho_{p\ mix}$

$$\rho_{p\ mix} = \frac{M_{mix}}{V_{mix}} = \frac{M_{soil} + M_{BC}}{V_{soil} + V_{BC}} = \frac{\left(\%_{vol}^{BC} \cdot \rho_{p\ BC}\right) + \left(\left(100 - \%_{vol}^{BC}\right) \cdot \rho_{p\ soil}\right)}{\%_{vol}^{BC} + \left(100 - \%_{vol}^{BC}\right)} \rightarrow$$

$$\rho_{p\ mix} = \frac{\left(\%_{vol}^{BC} \cdot \rho_{p\ BC}\right) + \left(\left(100 - \%_{vol}^{BC}\right) \cdot \rho_{p\ soil}\right)}{100}$$

Where:

$$\%_{vol}^{BC} = \frac{V_{BC}}{V_{mix}} = \frac{V_{BC}}{V_{soil} + V_{BC}} = \frac{\left(R_{mix}^{v} \cdot V_{soil}\right)}{V_{soil} + \left(R_{mix}^{v} \cdot V_{soil}\right)} = \frac{R_{mix}^{v}}{1 + R_{mix}^{v}}$$

and $R_{mix}^{v}$is the volumetric mixing rate as derived below.

$\rho_{p\ BC}$is the particle density of biochar, as determined by water pycnometry.

$\rho_{p\ soil}$ is the particle density of the unamended soil, as determined below.

Derivation of Volumetric mixing rate, R^v_{mix},

$R^v_{mix} = \frac{V_{BC}}{V_{soil}}$, where V_{soil} is the initial bulk (not particle) volume of soil.

R^g_{mix} is the gravimetric mixing rate (g BC/g soil).

$$R^g_{mix} = \frac{M_{BC}}{M_{soil}} = \frac{\left(\frac{M_{BC}}{Area}\right)}{\left(\frac{M_{soil}}{Area}\right)} = \frac{\left(\frac{M_{BC}}{Area}\right)}{\rho_{b\ TARGET} \cdot D_{furrow}}$$

where $\frac{M_{BC}}{Area}$ is selected in T/ha and converted to kg/m^2 for use in the equation, at the rate of:

$$1T/_{ha} = 1Mg/_{ha} = 1000kg/_{ha} = 1000kg/_{(100 * 100)m^2} = 0.1kg/_{m^2}$$

and D_{furrow} is the furrow or incorporation depth (set at 15cm).

$$R^g_{mix} = \frac{M_{BC}}{M_{soil}} = \left(\frac{M_{BC}}{M_{soil}}\right) \cdot \left(\frac{\rho_{b\ TARGET}}{\rho_{b\ TARGET}}\right)$$

$$R^g_{mix} \cdot \rho_{b\ TARGET} = \frac{M_{BC}}{M_{soil}} \cdot \rho_{b\ TARGET}$$

$$R^g_{mix} \cdot \rho_{b\ TARGET} = \frac{M_{BC}}{M_{soil}} \cdot \frac{M_{soil}}{V_{soil}} = \frac{M_{BC}}{V_{soil}}$$

$$R^g_{mix} \cdot \rho_{b\ TARGET} = \frac{M_{BC}}{V_{soil}} \cdot \left(\frac{\rho_{p\ BC}}{\rho_{p\ BC}}\right)$$

$$\frac{R^g_{mix} \cdot \rho_{b\ TARGET}}{\rho_{p\ BC}} = \frac{M_{BC}}{V_{soil} \cdot \rho_{p\ BC}} = \frac{M_{BC}}{V_{soil} \cdot \left(\frac{M_{BC}}{V_{BC}}\right)} = \frac{V_{BC}}{V_{soil}} = R^v_{mix}$$

$$R^v_{mix} = \frac{R^g_{mix} \cdot \rho_{b\ TARGET}}{\rho_{p\ BC}}$$

Calculation of the actual T/ha BC application rate of my cores and other studies

Below is an equation that was used in pre-calculations of soil packing density and biochar mixing rates:

$$R^{g}_{mix} = \frac{M_{BC}}{M_{soil}} = \frac{\left(\frac{M_{BC}}{Area}\right)}{\left(\frac{M_{soil}}{Area}\right)} = \frac{\left(\frac{M_{BC}}{Area}\right)}{\left(\frac{M_{soil}}{V_{soil}}\right) \cdot Depth} = \frac{\left(\frac{M_{BC}}{Area}\right)}{\rho_{b\ TARGET} \cdot Depth}$$

It was not possible to achieve the exact bulk density intended for each core, mainly due to swelling. Therefore, the intended application rate was not quite achieved. The above equation can be re-arranged to allow back-calculation of the true application rate $\frac{M_{BC}}{Area}$ using gravimetrically determined, swelling-adjusted bulk densities, and the actual gravimetric rate of BC application.

$$R^{g}_{mix\ actual} = \frac{M_{BC\ actual}}{M_{soil\ actual}} = \frac{\left(\frac{M_{BC}}{Area}\right)_{actual}}{\rho_{b\ actual} \cdot D_{furrow}}$$

$$\left(\frac{M_{BC}}{Area}\right)_{actual} = \frac{M_{BC\ actual}}{M_{soil\ actual}} \cdot \rho_{b\ actual} \cdot D_{furrow}$$

Where $\frac{M_{BC}}{Area}$ is the amount of BC expressed in kg/m^2 or T/ha.

The same equation can be used to convert T/ha and g BC/g soil measurements from other studies.

Appendix D

During and after the WR experiment adjustments were made to Soil O's bulk density calculations because of revisions to soil volume calculations (describing the soil swelled above the ring tops with a combined spherical cap and cylindrical geometry instead of cylindrical geometry only), and revisions to dry soil weights after post-experiment oven-drying showed that I apparently underestimated gravimetric water content at the time of packing.

These changes to my calculations revealed that there were indeed VWC differences between the lower two BC amendment rates (5 and 10 T/ha) that warranted my investigation with Soil M. I should have done my texture and OM tests before beginning my pressure plate tests, but it seemed like a small detail to sacrifice for starting my experiments earlier. Those tests showed the soils to be so dissimilar that anything seen in one soil should not have been inferred to indicate anything about the other soil.

Belated changes were also made to soil particle density measurements to account for newly-measured OM contents, but these do not affect WR measurements of VWC, which depend only on calculations of dry soil weight and soil volume. However, with the updated particle density results the true porosities of my treatments ended up much differently than the 0.58 m^3/m^3

Appendix E

Statistical significance

Formula for the unequal variance t-test (Bluman, 2007):

$$\left((\bar{X}_1 - \bar{X}_2) - t_{\alpha/2} \cdot \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}\right) < \mu_1 - \mu_2 < \left((\bar{X}_1 - \bar{X}_2) + t_{\alpha/2} \cdot \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}\right)$$

Where: $\bar{X}$ are the sample means being tested; $t_{\alpha/2}$ is the t-value from a t-test table, e.g. for 95% two-tailed confidence ($\alpha/2$= 0.05) at $n-1$ degrees of freedom; s is the standard deviation of each sample mean; and µ are the true population means of treatments 1 and 2.

Verification of Excel calculations

Microsoft Excel's output from the unequal variance, two-tailed t-test is given in terms of P values, where any result showing P<0.05 meets my confidence criteria. An analysis of Ksat results with Excel indicated that significant differences existed between treatments 0 & 100 and 10 & 100. My calculations using the above formulae, a t-value of 2.571 ($^{\alpha}/_{2}$ = 0.05, 5 degrees of freedom) showed the same results:

		Excel calculations	My calculations:			
Treatments Compared (T/ha)		Confidence (α=1- P) that means are signicantly different. P=	$t_{\alpha/2} \cdot \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$	There is 95% confidence that µ1-µ2 falls within the interval below:		
0	10	0.928	1.358	-1.402	<µ1-µ2<	1.313
0	50	0.134	1.328	-2.087		0.569
0	100	0.040	1.599	-3.275		-0.077
10	50	0.134	1.292	-2.006		0.578
10	100	0.042	1.569	-3.200		-0.062
50	100	0.204	1.544	-2.461		0.626

Standard Deviation and Standard Error

Standard deviation, *s*, is calculated for a sample mean as shown below, where X_i are all sample values, $\bar{X}$ is the mean of all samples, and *n* is the number of samples:

$$s = \sqrt{\frac{\sum_{i \to n}(X_i - \bar{X})}{n-1}}$$

Standard Error, SE:

$$SE = \sigma_{\bar{x}} = \frac{s}{\sqrt{n}}.$$

<u>Cohen's (1988) statistical power analysis</u>

Using values for effect size, *d,* calculated from my data using the equations shown below, and a desired confidence level (power) of 95% (0.95), the number of samples required is approximated by extrapolating from the table below.

Power Tables for Effect Size d

(from Cohen 1988, pg. 55) **via Hoffmann, 2012**

two-tailed α = .05 or one-tailed α = .025

	d										
Power	**.10**	**.20**	**.30**	**.40**	**.50**	**.60**	**.70**	**.80**	**1.0**	**1.20**	**1.40**
.90	2102	526	234	132	85	59	44	34	22	16	12
.95	2600	651	290	163	105	73	54	42	37	19	14
.99	3675	920	409	231	148	103	76	58	38	27	20

If the data shown above is plotted, the curve for a power level of 95% has the following equation:

$$n_{minimum\ for\ P=0.05} = 28.304d^{-1.946}$$

$$d = (\bar{x}_1 - \bar{x}_2)/s_c$$

$$s_c = \sqrt{\left(\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2}\right)}$$

$$s_1^2 = \frac{1}{n_1 - 1}\sum_{i \to n}\left((x_{1,i} - \bar{x}_1)^2\right)$$

Where: d represents the effect size shown between the two sample means being tested (calculated from my data); s_c is Cohen's calculation of pooled standard deviation.

Appendix F

Packing Summary of WR Cores

Soil O's packing did not change after swelling initially so it only has 2 measurements, whereas Soil M swelled then shrank, so it has three measurements.

Soil O WR, Control - 0 T/ha

0	Mean	CV%	Mean θ	CV%
Initial	1114.9	2.4	0.505	2.4
Final	1028.5	2.0	0.543	1.7

Soil O WR, 5 T/ha

	Mean	CV%	Mean θ	CV%	Mean T/ha	CV%
Initial	1142.4	2.3	0.492	2.4	5.21	2.3
Final	1043.9	1.6	0.536	1.4	4.76	1.6

Soil O WR, 10 T/ha

	Mean	CV%	Mean θ	CV%	Mean T/ha	CV%
Initial	1113.8	2.7	0.504	2.7	10.19	2.7
Final	1018.7	2.3	0.546	1.9	9.32	2.3

Soil O WR, 50 T/ha

	Mean	CV%	Mean θ	CV%	Mean T/ha	CV%
Initial	1102.7	1.8	0.505	1.8	51.69	1.8
Final	980.6	1.6	0.560	1.3	45.97	1.6

Soil M WR, Control - 0 T/ha

	Mean ρ_b	CV	Mean θ	CV
Initial	1482.7	1.6	0.417	2.2
Post-saturation	1376.1	1.4	0.459	1.6
Final	1490.2	1.7	0.414	2.3

Soil M WR, 10 T/ha

	Mean ρ_b	CV	Mean θ	CV	Mean T/ha	CV
Initial	1478.8	1.9	0.417	2.7	11.68	1.9
Post-saturation	1366.9	2.3	0.461	2.7	10.79	2.3
Final	1470.3	2.5	0.420	3.4	11.61	2.4

Soil M WR, 50 T/ha

	Mean	CV	Mean θ	CV	Mean T/ha	CV
Initial	1350.1	1.8	0.462	2.1	51.88	1.7
Post-saturation	1234.0	1.7	0.509	1.6	47.42	1.5
Final	1324.3	1.3	0.473	1.5	50.89	1.2

Soil M WR, 100 T/ha

	Mean	CV	Mean θ	CV	Mean T/ha	CV
Initial	1313.9	1.1	0.470	1.2	99.35	1.1
Post-saturation	1193.4	1.2	0.519	1.1	90.24	1.2
Final	1264.7	1.2	0.490	1.2	95.63	1.2

Appendix G

Water filled porosity: T-test values of differences between mean WFP of treatments

Tables show P-values from two-tailed, unequal variance t-tests of differences between sample means. Highlighting is colour-coded to separate 99.9% (blue), 99% (green), 95% (red), and 90% (grey) levels of confidence that the sample means of treatments being compared are significantly different.

Soil O

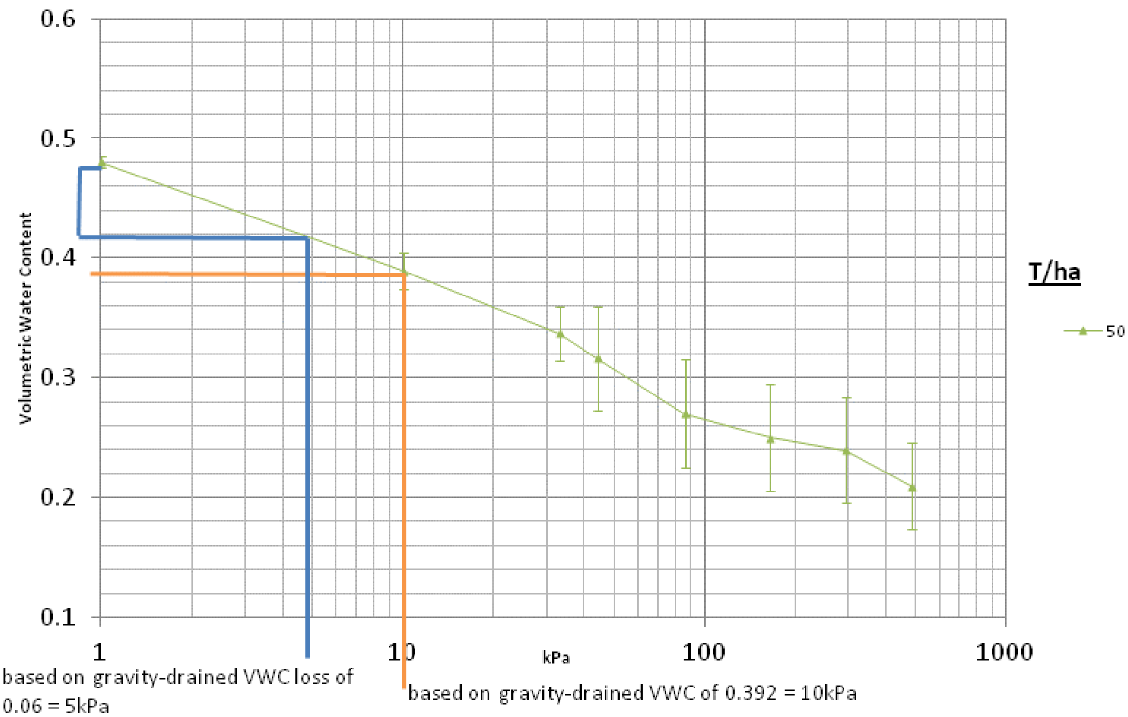
Treatments Compared (T/ha)		Tension (kPa)											
		0	5	10	33	44	62	76	95	128	200	300	483
		P-values from two-tailed, unequal variance t-tests											
0	5	1.000	1.000	0.344	0.095	0.126	0.141	0.143	0.176	0.222	0.295	0.330	0.296
0	10	1.000	1.000	0.870	0.104	0.084	0.072	0.086	0.100	0.248	0.368	0.390	0.288
0	50	1.000	1.0000	0.8698	0.104	0.084	0.072	0.086	0.100	0.248	0.368	0.390	0.288
5	10	1.000	1.000	0.374	0.970	0.465	0.296	0.456	0.426	0.886	0.987	0.942	0.716
5	50	1.000	1.0000	0.3739	0.197	0.003	0.003	0.004	0.008	0.023	0.052	0.046	0.028
10	50	1.000	1.000	0.913	0.206	0.001	0.001	0.005	0.009	0.058	0.119	0.106	0.079

Soil M

Treatments Compared (T/ha)		Tension (kPa)							
		Saturated	10kPa	33kPa	44kPa	86kPa	165kPa	293kPa	483kPa
		P-values from two-tailed, unequal variance t-tests							
0	10	0.7664	0.3454	0.8531	0.4905	0.4908	0.4479	0.4588	0.4287
0	50	0.8724	0.7372	0.7650	0.9838	0.7026	0.8506	0.8804	0.9071
0	100	0.2892	0.4078	0.9365	0.6206	0.3493	0.1787	0.2022	0.1849
10	50	0.6339	0.2541	0.5139	0.5621	0.8657	0.7076	0.6950	0.6519
10	100	0.2224	0.0407	0.6997	0.7215	0.8828	0.5491	0.5888	0.6233
50	100	0.1984	0.1285	0.6885	0.6949	0.7766	0.4564	0.4724	0.4505

Appendix H

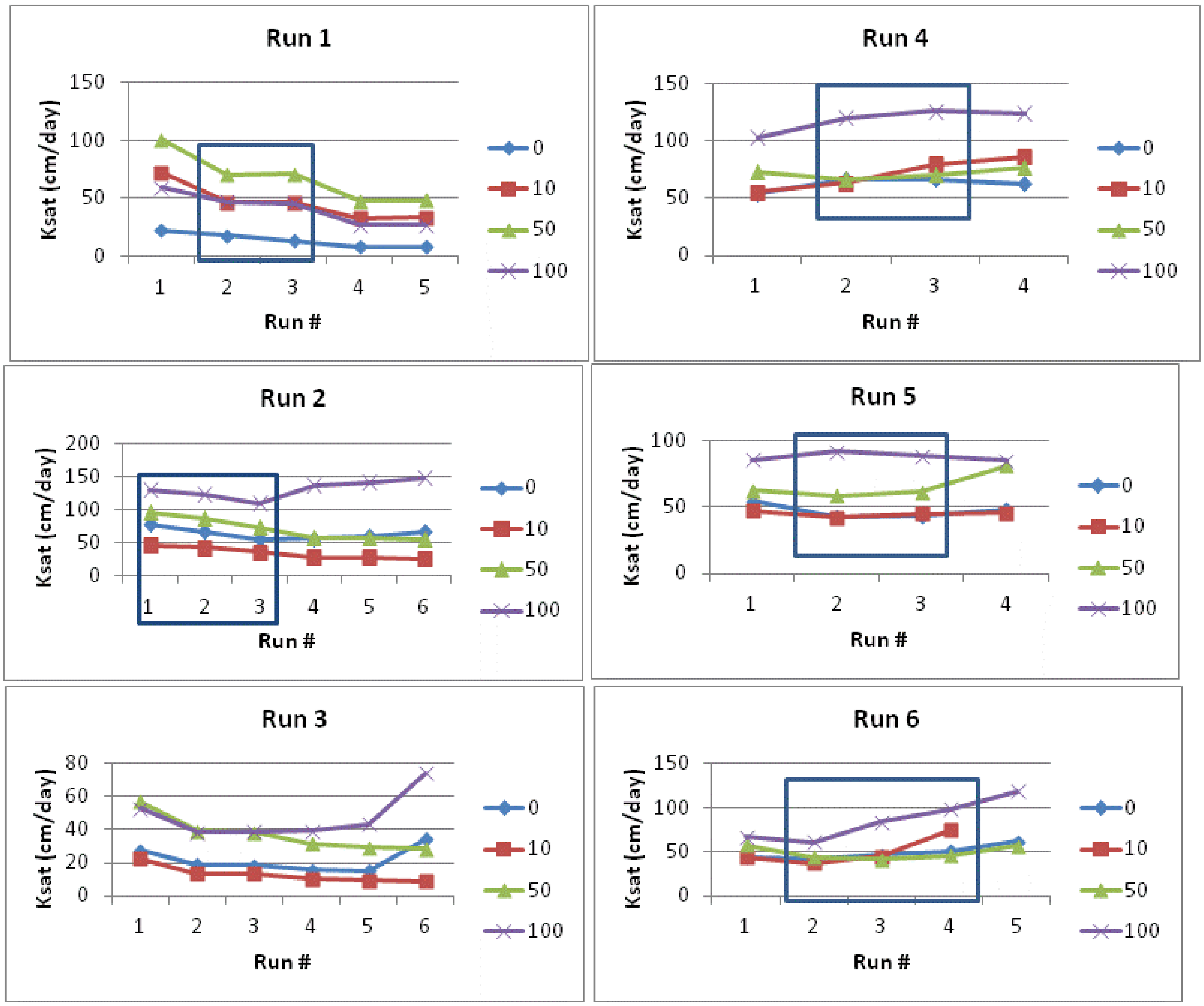
Extrapolating the VWC measurements from Ksat tubes onto the WR curve made with Soil M. In one method I subtracted the VWC loss in the drained Ksat tubes from the saturated VWC of the corresponding treatments. In the other method I simply worked across from the drained Ksat VWC. The former method achieved closer agreement with Brady and Weil's prediction of 5 kPa as the gravity-drained tension equivalent.



Treatment (T/ha)	Extrapolated tension equivalent (kPa) based on:	
	VWC	VWC decrease
0	5	5
10	3	7
50	10	5
100	2	4

Appendix I

Variations in Ksat seen over time during each replication



Appendix J

Mean VWC for each treatment at each tension for Soil O:

	Tension (kPa)											
T/ha:	1	5	10	33	44	62	76	95	128	200	300	483
0	0.558	0.556	0.544	0.516	0.496	0.487	0.478	0.468	0.451	0.435	0.432	0.417
5	0.556	0.555	0.545	0.526	0.516	0.504	0.495	0.484	0.464	0.445	0.440	0.426
10	0.572	0.567	0.553	0.541	0.531	0.522	0.512	0.502	0.475	0.453	0.449	0.440
50	0.582	0.577	0.565	0.533	0.498	0.491	0.482	0.474	0.455	0.440	0.433	0.416

Mean VWC for each treatment at each tension for Soil M:

	Tension (kPa)							
T/ha	1	10	33	44	86	165	293	483
0	0.460	0.384	0.316	0.304	0.277	0.247	0.235	0.205
10	0.455	0.368	0.312	0.281	0.253	0.224	0.214	0.186
50	0.480	0.389	0.337	0.316	0.270	0.250	0.240	0.210
100	0.508	0.415	0.332	0.300	0.257	0.216	0.207	0.183