Soil Physical Characteristics of an Aeric Ochraqualf amended with Biochar

THESIS

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By

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Abstract

Incorporation of biochar into agricultural soils has been proposed as a potential best management practice (BMP) to increase crop yield and sequester atmospheric carbon (C). Furthermore, the production of biochar, referred to as pyrolysis, yields biofuel that can offset fossil fuels. Current research involving biochar and soil is mainly limited to greenhouse experiments and a few short-term field scale experiments. Here, biochar was incorporated into a field-scale corn (*Zea mays*)/soybean (*Glycine max*) system for analysis of soil mechanical and hydrological properties correlated with crop yield. A randomized complete block design was implemented with three biochar application rates: 0 Mg ha^{-1} (TC), 5 Mg ha^{-1} (TB5), and 25 Mg ha^{-1} (TB25). All plots were tilled using a tractor and rotovator in order to attain uniform incorporation of biochar. A small adjacent field was managed with no-till practices (NTC) to quantify the effects of tillage. Biochar is an effective soil conditioner, evident by TB25 soil bulk density 9% and 18.5% less than that of TC and NTC, respectively. Analysis of soil pore size distribution resulted in TB25 with significantly increased macro-pores (1500 µm) related to water transmission and micro-pores (0.5 µm) related to water retention. Furthermore, plant available water capacity (AWC) of TB25 significantly increased by 9.6% and 29% over TC and NTC, respectively. Biochar amendment (TB25) increased saturated hydraulic conductivity (K_s) by 33% and 78% over TC and NTC, respectively. Soybean above-ground biomass and grain yield of TB25 resulted in respective 12.3% and 12.5% increases over TC. Correlation and linear regression analysis revealed significant positive trends with AWC, soil bulk density, total porosity, among other properties. Results suggest biochar is an effective soil amendment for temperate agricultural soils, yet long-term research will provide additional insight into the potential for biochar to improve soil quality, sequester atmospheric carbon, and enhance crop yield.

Dedication

This document is dedicated to my wife, Katelyn Krivchenia, and our family.

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Chapter 1: Introduction

Introduction and global context

In a world of increasing population and growing economies, global issues including climate change, food insecurity and energy demand necessitate identification of innovative techniques of sustainable management of soils. Expectations for agricultural soils to maintain, or even improve, quality while sequestering carbon (C), increasing crop yield and producing biofuels are challenged by heavy demands of the projected population increases (United Nations 2011) while approximately 1 in 7 people are already food insecure (FAO 2010). Few management practices can have measureable impacts on all three issues as significant as biochar production and use as a soil amendment. When combined with proper nutrient amounts, biochar amendment can increase crop yield 25–250% (Jha et al. 2010), with the most improvement typically occurring on highly degraded tropical soils. Since well over half the population inhabits tropical regions of the world, biochar soil amendment addresses agricultural sustainability through improved soil quality. Here, a review and discussion of changes in soil physical properties from biochar amendment precedes a research proposal to measure its impact on quality of a temperate agricultural soil. As a preamble, a brief description of the origin of biochar and historical perspectives are discussed.

1.1 Terra Preta do Índio

Biochar soil amendment is envisaged as a technique to reproduce, in current agricultural soils, some of the characteristics of Amazonian Dark Earth soils (ADEs) formed by pre-Columbian

Amazonian peoples (Glaser 2007). Sites of these fertile soils range in area from 0.5 ha up to 350 ha and are found along the Amazon and connecting rivers (Paz-Rivera 2009). Evident by shards of clay pottery and other artifacts (Meggers 1995), *terra preta do Índio* are anthrosols developed from the accumulation of household and community waste. Cooking fires, bon fires, and slash-and-burn agricultural practices produced the charcoal and ash visibile in these dark tropical soils. Hence, the idea of adding charcoal, recently referred to as biochar, to soils of managed ecosystems is gaining momentum.

Biochar and charcoal are differentiated both by production methods and their intended functional use, even though they are physically and chemically similar types of black C. Charcoal is produced at an estimated temperature, sometimes chemically treated, and used for cooking, while modern biochar is produced at a specific temperature and with the intention of improving soil properties, sequestering C, and mitigating various anthropogenic processes known to be environmentally hazardous. Despite intention, both have been used in soil research and other contexts. The International Biochar Initiative (IBI) is currently developing 'The Biochar Product Standard,' which will more clearly define properties of biochar with respect to its intended purpose. Regardless of definition, *terra preta* soils contain up to 70 times the amount of black C in surrounding soils, but archaeological evidence suggests fertility is not simply the result of charcoal amendment.

Evidence of organic diversity including human and animal excrement, various types of mammal and fish bones, and terrestrial and aquatic plant biomass suggests soil enrichment may have been intentional. Although, soil enrichment towards the currently observed quality of ADEs is unlikely, which is why German (2003) focused on the specific cultural behaviors that individually may have contributed to improved soil quality. Regardless, studying quality differences between *terra preta* and adjacent unamended soils can provide insight into potential management techniques that can be incorporated into modern agriculture.

1.2 Terra Preta Soil Quality

Analyses of *terra preta* soils indicate significant gains in quality compared to adjacent unamended soils. ADEs exhibit a higher stable amount of soil organic matter (SOM) compared to surrounding soils (Kamf 2003). Observed soil organic carbon (SOC) concentrations are an order of magnitude higher (Novotny 2007). In addition to SOC, higher amounts of nutrients (i.e. potassium, phosphorus and zinc) were also measured and corroborated with increased rice (*Oryza sativa*) and bean (*Phaseolus vulgaris*) yields (Lehmann 2003). The high nutrient concentration is attributed to improved cation exchance capacity (CEC) from the combined effect of SOM and charcoal inputs (Glaser et al. 2002). Biochar can be better than most forms of SOM at holding nutrients (Sombroek 2003). Nutrient retention and pH increases likely impact soil microbiology and the role of microbial processes in soil nutrient dynamics (Glaser 2007). While soils of the humid tropics (such as those in the Amazon) are typically acidic, *terra preta* soils, still acidic, have a higher pH and, therefore, buffer plants against aluminum toxicity (Chan et al. 2007). Most biochars are alkaline, but pH values between 4 and 12 can be attained when producing a biochar (Lehmann 2007). The pH of biochar itself is not indicative of it's liming value (Lehmann and Joseph 2009), but is determined by the carbonate concentration (Van Zweiten et al. 2007). With the addition of many different types of amendments and a long period for ADE soils to mature, 500 to 7,000 year old radio carbon dated charcoal (Neves et al. 2003), it is necessary to study more short-term changes in soil properties when amended with biochar.

1.3 Biochar Carbon Sequestration

Replenishing SOM of highly degraded soils, especially for mitigating anthropogenic climate change, is a challenging task (Lal 2009). Biochar is described as a soil amendment with the potential to preserve and enhance SOM, increase soil fertility and sequester C. It is formed in a heated anaerobic environment, while syngas and bio-oil are extracted from the organic matter feedstock, leaving behind the black porous substance (Lehmann 2006). The C concentration of biochar can range from 40% produced from poultry litter to 78% produced from pine chip (Gaskin et al. 2008), which is C that would otherwise be emitted as CO_2 into the atmosphere during decomposition. Slash-and-burn techniques used by many farmers of the tropics convert about 3% of the original C pool into biochar (Glaser et al. 2002). If those farmers switched to a slash-and-char practice (Lehmann et al. 2002), between 5 and 40 Mg C ha^{-1} could be sequestered (Lehmann and Rondon 2005).

There are two main mechanisms in which the production and subsequent incorporation of biochar into soils sequesters C from the atmospheric C pool for the purpose of climate change mitigation. The C is a recalcitrant form of soil organic carbon (SOC) which in of itself increases the mean residence time (MRT) of the terrestrial C pool by reducing the amount of C susceptible to biotic and abiotic decomposition, thereby reducing total soil C emission rates. Additionally, black C, such as biochar, can occlude within soil aggregates which reduces accessibility of both abiotic and biotic decomposition mechanisms, thereby reducing C emissions from the global soil pool to the global atmospheric pool.

Biochar characteristics, including physical structure and chemical reactivity parameters, largely depend on the type of biomass feedstock and production parameters such as air exposure, duration of combustion, and temperature (Pandolfo et al. 1994; Lehmann et al. 2002). A common property of biochar is its resistance to decomposition from soil biota and slow abiotic mineralization (Kuzyakov et al. 2009; Cheng et al. 2006). This recalcitrant C amended to soils increases the mean residence time (MRT) of C in the SOC pool. Further protection of C occurs during soil aggregation which could extend MRT of biochar with overall C sequestration estimated at 5.4 Mg C ha^{-1} yr^{-1} (Lehmann and Rondon 2006) and potentially 1 Gt C yr^{-1} by 2050 (Lehmann 2009). Soil disruptive land-use change negates C sequestration through aggregation, indicating the need for a strategy in regards to the practical issues related to the overall process of biochar soil amendment, from feedstock source, preparation and production to transportation and soil incorporation. The goal is to maximize C sequestration, improve soil quality, and reduce risks of food insecurity.

Biochar has a wide applicability in the efforts to mitigate climate change and improve living conditions of a significant portion of the world population. An estimated 2.5 billion people use cook stoves which burn biomass to produce heat (Saldiva and Miraglia 2004). Indoor pollution, leading to severe health concerns (including 1.6 million deaths per year), could be mitigated through improved cook stoves such as biochar producing cookstoves or solar cookstoves (Ramanathan and Balakrishnan 2007). Adoption of improved cook stoves would also reduce black C emissions, which may have a significant effect on glacial melting and global warming (Ramanathan and Carmichael 2008).

2. Biochar and soil physical characteristics

Biochar soil amendment can improve nutrient retention, crop yield and other soil chemical characteristics. However, research on similar impacts on soil physical characteristics is sparse. The study of the structure of biochar suggests that physical characteristics of such amended soils can be significantly improved (Glaser et al. 2002; Jha et al. 2010), including those of some temperate soils (Atkinson et al. 2010). Thus, the objective of this review is to collate and synthesize the available literature regarding soil mechanical and hydrological properties with a focus on moisture release characteristics, and water transmission impacted by biochar soil amendment. Attendant changes in crop yield and ancillary benefits related to improved soil quality include changes in soil biology, sorption of pollutants, and soil stabilization are also discussed. Table 1 summarizes relevant soil properties while Table 2 highlights specific crop yield trends and related mechanisms with regards to the use of biochar amendment.

2.1 Soil Mechanical Properties

It is well established that soil physical properties have important implications for plant growth and water management. Healthy agricultural soils are indicated by a range of parameters, upon which particle size distribution (texture) defines baseline functional range. Bulk density (ρ_b) and total porosity (f_t) tend to correlate inversely and indicate the degree of compaction, aeration and moisture retention in soils. Soil pore size distribution (PSD) indicates aeration and moisture flow (transmission pores), water retention (storage pores), and ionic diffusion (residual pores) (Greenland 1977). Specific surface area provides insight into potential reactivity of soils. Soil aggregate formation is an important process regarding resistance to erosional processes, moisture and nutrient retention, C sequestration and microhabitat diversity. Soil strength is an indicator of resistance to deformation by machinery and plant root penetration.

2.1.1 Particle Size Distribution:

As an inorganic soil property formed from the weathering of parent material, the texture of a soil provides a foundation in which other soil properties may be influenced by natural processes and management practices. Like many management practices involving organic material, biochar has no effect on soil particle size distribution. However, many soil properties determined by texture are influenced by biochar. For example, under field conditions, large biochar particles absorbed and retained more nitrogen (N) and potassium (K) than smaller particles (Dunisch et al. 2007). Depending on feedstock and pyrolysis processes, biochar particles, typically between 0.6 mm and 4.75 mm, tend to be much larger than soil components (Downie et al. 2009). Many studies crush and sieve biochar to attain a more effective soil conditioner, but a researchable question is determining effective biochar particle size distribution in regards to managing the soil properties in relation to soil texture.

2.1.2 Soil Bulk Density and Total Porosity

During pyrolysis, increasing temperature causes volatile organic compounds to be forced out of the feedstock, resulting in dramatic increases in porosity and surface area (Bagreev et al. 2001). Biochar, being lightweight and voluminous, tends to decrease ρ_b of agricultural soils (Laird et al. 2010). The ρ_b of biochar ranges from 0.3 and 0.43 Mg m^{-3} (Pastor-Villegas et al. 2006), compared to 1.0 – 1.5 Mg m^{-3} for agricultural soils (Lal and Shukla 2004). Thus, as Table 1 elicits, there is a well-established trend of decreasing ρ_b with increasing concentration of biochar (Brockhoff et al. 2010; Oguntunde et al. 2008). Therefore, Biochar, as an effective soil conditioner, can provide relief for compacted or gravelly agricultural soils.

Soil f_t and pore size distribution are important characteristics regarding water transmission and retention, aeration, and habitat for microorganisms. With decreased soil ρ_b from biochar amendment, f_t is expected to increase. Of twelve charcoal kiln sites, mean f_t increased by over 10% compared to surrounding soils (Oguntunde et al. 2008). The benefit of charcoal amendment over slash-and-burn practices in the tropics in regards to increased f_t and macroporosity, which enhance water infiltration and mitigate runoff from erosional processes. Laboratory analyses to assess pore connectivity and pore size distribution of biochar particles (4 – 5 mm) indicate accessibility to interior surfaces by both soil solution and microorganisms (Bird et al. 2008).

Research related to biochar extends outside of agricultural soils to specific environmental applications. In search of effective amendments for bauxite processing sand, a 6-week incubation study indicated reductions in ρ_b of 6% and 12.7% and the attendant increases in f_t of 3% and 10.8% with biochar rates equivalent to 40 and 80 Mg ha^{-1} (Jones et al. 2010). Equivalent amendment rates of biosolids, mushroom compost, and green waste compost produced similar results, but biochar had the greatest impact on shifting the pore size distribution from macropores (> 30 µm) to micropores (0.1 – 29 µm). Thus, biochar provides increased habitat space for bacteria, algae, fungi, actinomycetes, and lichens (Downie et al. 2009). Since moisture content and pH often differ between biochar and adjacent soil, microorganism diversity, behavior, and abundance may also differ (Thies and Rillig 2009).

2.1.3 Aggregation

Soil aggregation is a natural process involving the construction of secondary particles from primary particles exposed to physico-chemical and biological processes. The continuous bonding of clay domains, polyvalent cations, and organic matter (OM), depending on the amount of labile OM, results in hierarchical micro-aggregation, in which the bonds within aggregates are stronger than those between aggregates (Edwards and Bremner 1967). Macro-aggregates (> 250 µm) tend to be less stable than micro-aggregates (< 250 µm) with respect to the impact of land management practices. Biotic and abiotic decomposition processes are inhibited by stable aggregates, thereby providing protection and, therefore, C sequestration (Six et al. 2000; Bronick and Lal 2005).

Biochar particles may have an important role in C sequestration, evident by increasing concentrations of occluded black C with decreasing aggregate size (Brodowski et al. 2006). Photo-oxidation of organic compounds may be the mechanism causing the increased biochar concentration in aggregates (Clough and Skjemstad 2000; Carter et al. 2002). While tillage has little impact on micro-aggregation, burning soil causes an increased proportion of macro-aggregates and decreased proportion of micro-aggregates, resulting in increased water retention at low pF (suction) values (Gonzalez-Pelayo et al. 2006). Biochar is an ineffective amendment to induce micro-aggregation, unless combined with a more labile C source (Watts et al. 2005; Busscher et al. 2009). Stable forms of OM, such as coal-derived humic acids, can improve macro-aggregate stability (Mbagwu and Piccolo 1997). Opportunities to research the impact of biochar on binding agents can substantially enhance the literature in regards to aggregate formation. For example, biochar influence on the concentration of humic substances and their molecular sizes may impact aggregate formation (Piccolo and Mbagwu 1990).

In respect to aggregation, there exist positive interactions between biochar amendment and soil biota. Warnock et al. (2007) proposed four different hypotheses of positive interactions between biochar and mycorrhizal fungi, which also accentuate aggregation (Tisdall and Oades 1982; Miller and Jastrow 1990; Rillig et al. 2002). Small microbial communities with growth rates higher than those supported by humus are supported by biochar after slash-and-burn methods are conducted (Pietikainen et al. 2000). Earthworms also increase stable aggregates and help mix biochar and soil through ingestion (Topoliantz et al. 2006; Topoliantz and Ponge 2003).

2.1.4 Soil Strength

Soil strength can be characterized by measuring penetration resistance and tensile strength, which are also indicators of aggregate strength. A crushed pecan (*Carya illinoinensis*) biochar mixed with a Norfolk loamy sand and incubated in columns displayed a significantly lower penetration resistance than the control, but only at the highest rate of 44 Mg ha^{-1} biochar (Busscher et al. 2009). Soil tensile strength tends to decrease with increasing biochar concentration, evident in a hard-setting Australian Alfisol (Chan et al. 2007; Chan et al. 2008). Aygun et al. (2003) reported biochar with high lignin and low ash contents, which together indicate high mechanical strength, a determinant of the recalcitrance against decomposition from weathering and erosion. These findings agree with observed persistence of biochar in *terra preta* soils (Glaser et al. 2002).

2.1.5 Surface Area

Specific surface area is important regarding CEC improvements and sorption dynamics in soils, and is typically measured on a mass basis (m^2 g^{-1}) using nitrogen (N_2), ethylene glycol monoethyl ether (EGME), or iodine adsorption methods (Soil Methods text). Soil particle size distribution, and mainly the clay content, determine the surface area of a soil. Biochar has an abundance of micropores that tend to increase total surface area, which can provide additional (CEC), nutrient and water retention, and filtering capacity (Glaser et al 2002; Lal and Shukla 2004).

Biochar impact on soil surface area depends mainly on the biochar characteristics and the soil clay content. A loamy Mollisol increased in surface area from 130 to 153 m^2 g^{-1} with a 20 g kg^{-1} biochar rate, indicating an effective biochar surface area of 1150 m^2 g^{-1} (Laird et al. 2010). Extreme values of the surface of biochar include 1,500 m^2 g^{-1} (Downie et al. 2009), using EGME technique compared with only 21.6 m^2 g^{-1} for a switchgrass (*Panicum virgatum*) biochar with a N_2 gas sorption method (Brockhoff 2010). Such contrasting differences are not likely due to methodology, but to the heterogenous nature of biochar. Depending on numerous factors, clay particles have a wide range of surface area ranging from 5 to 750 m^2 g^{-1} (Troeh and Thompson 2005). The high surface area of biochar used as a soil amendment produces favorable impact when applied to a coarse-textured or a sandy soil (Liang et al. 2006).

2.2 Soil Moisture Retention

Soil moisture characteristics are among primary indicators of soil physical quality. Lab procedures to measure parameters, such as moisture retention, involve soil cores either taken from field sites or packed using bulk soil. Packed cores are advantageous for biochar analysis of moisture retention because an exact ratio of amendment to soil can be measured. Cores taken from the field are more representative of the pore size distribution, and therefore, reflect more realistic changes in moisture retention. An *in situ* assessment of field capacity (FC) is even more representative of soil's available water capacity (AWC) since it includes the entire soil profile and is done in the field.

Newly pyrolyzed biochar is initially hydrophobic, as observed by hydrophobic molecule sorption, caused by chemical reactions during the pyrolysis process (Lebo et al. 2003; Bornemann et al. 2007). As biochar oxidizes, negatively charged functional groups bond to the surface of the biochar particle, thereby mitigating the hydrophobic behavior (Cheng et al. 2006; Liang et al. 2006). Observed increases in water retention confirm this change.

The impact of biochar on moisture retention in sandy soils suggests that dry climates with high sand content would benefit significantly from amendment (Blackwell et al., 2010). Biochar characterisitics and amended medium properties influence moisture retention, evident by a range of increases in AWC from 18% to 370%, and increases in FC up to 82% (Jones et al. 2010; Brockhoff et al. 2010; Tryon 1948). Biochar characteristics play an important role in AWC, evident by no significant change when a loamy sand was amended with pecan biochar up to 44 Mg ha^{-1} (Busscher et al. 2010). Potential improvements in water holding capacity likely depend on biochar feedstock, charring conditions and soil properties (Novak et al. 2009).

Some studies suggest that the biochar pore size distribution may have a particularly important role in determining changes in plant AWC. A study on packed soil columns of a Midwestern Mollisol and various hardwood biochar treatments indicated a 15% increase in water retention at the 30 Mg ha^{-1} equivalent, but no significant differences were detected at -0.033 MPa and -1.5 MPa soil water matric potentials (Laird et al. 2010). It was concluded that biochar has the potential to increase crop yields during water stress, as evident by 13% and 10% more water in -0.1 and -0.5 MPa of soil matric potential for the 30 Mg ha^{-1} treatment. Previous studies also suggest that biochar has a significant water holding capacity, especially with respect to other porous materials (Iswaran et al. 1980; Pietikainen et al. 2000).

Table 1. Physical properties and moisture characteristics related to biochar amendment.

Soil	**Biochar Description**	**Biochar Rate ($Mg\ ha^{-1}$)**	**ρ_b ($Mg\ m^{-3}$)**	**f_t (v/v)**	**SSA ($m^2\ g^{-1}$)**	**Water Infiltration**	**K_s ($cm\ h^{-1}$)**	**FC (v/v)**	**AWC (v/v)**	**Reference**
Loamy sand with poor structure	Charcoal kiln site	AFS CSS	9% decrease	10% increase		CSS has higher cumaltive infiltration at all times	87% increase of mean			Oguntunde et al. 2008
Mesic Typic Hapludolls	Mixed hardwood traditional kiln < 0.5 mm	0 – 20			18 % increase Calculated value of 1150		No significant effects observed	10 – 15 % above control	-1 and -5 MPa significantly higher	Laird et al. 2010
Calcareous sand Mostly coarse and medium size	Switchgrass at 500 °C	0 – 25 % by volume	Decrease 1.75 – 1.57		21.6		Decrease 84.8 – 6.6		Increase 0.07 – 0.26	Brockhoff 2010
Northern Laos Clay/clay loam Sandy clay loam	Woody products Earth mound method < 2mm	0 – 16	43.8 g cm^{-2}			Increased permeability & WHC impacts plant AWC	78% increase with highest rate			Asai 2009
Silt Loam	Hardwood at 400 °C < 10 mm	0 – 9	3.8% decrease	3.7% increase	3.6				11% increase in WHC	Karhu 2011

AFS = adjacent field site, CSS = charcoal site soil, ρ_b = bulk density, f_t = total porosity, SSA = specific surface area, FC = field capacity, AWC = plant available water capacity, WHC = water holding capacity, K_s = saturated hydraulic conductivity

2.3 Water Transmission

Soil erosion and runoff mainly result from exceeding the infiltration capacity determined by the intensity of a rainfall event and the soil structure. Managing agricultural soils to improve water infiltration has beneficial impacts on soil quality, which may impact crop yield. Infiltration can be measured in the field, which provides valuable information about the water intake rate of a soil profile. As a substitute, saturated hydraulic conductivity (K_s) can be measured in the lab using cores of soil from multiple depths. Both methods produce highly variable results, whereby more certain results can be obtained by increasing the measured area, the time of saturation, and the number of samples (Bouwer 1986).

In laboratory experiments, biochar can significantly change K_s at rates as low as 16 Mg ha^{-1}. Brockhoff et al. (2010) observed saturated flow in biochar sand mixtures of rates ranging from 0 to 25% by volume. In sand, increasing biochar concentration from 0 to 150 Mg ha^{-1} correlates linearly with decreasing K_s values, 85 cm h^{-1} to 7 cm h^{-1}, respectively. Improvements in soil water permeability and water holding capacity of an upland rice system were significant at 16 Mg ha^{-1} rate (Asai et al. 2009). In a study using packed columns, all but one amended treatment of biochar and switchgrass increased water infiltration rate significantly ($p = 0.1$) (Busscher et al. 2009), which was attributed to a reduction in soil strength. Additionally, bagasse biochar reduced water permeability which was attributed to the increased available moisture of a Shimajiri maji soil (Chen et al. 2010).

A study in Ghana on 12 charcoal production sites compared hydro-physical properties of charcoal soil sites (CSS) and adjacent field sites (AFS). On average, 9% lower ρ_b and 10.7% higher f_t of CSS supported the 87.9% increase in K_s (Oguntunde et al. 2008). Soils were sandy in texture with significantly higher sand content in CSS than AFS, likely resultant of exposure to high temperatures causing clay and silt particle fusion. These stark differences indicate high amounts of charcoal in CSS, although the author sites comparable results (Agyare 2004). Using these data, a simulation of high (200 mm h^{-1}) and moderate (100 mm h^{-1}) rainfall events indicated in the CSS a reduction of runoff by 37 and 18%, respectively (Ayodele et al. 2009). Authors cited this improvement as a distinct and significant difference from the behavior of soils affected by fire, as in those in slash-and-burn agriculture, which typically have increased surface runoff and erosion (Oguntunde et al. 2008). Caution was expressed about conclusions at the plot scale, as a watershed response is more important.

2.4 Crop Yield

As global population continues to increase, improving crop yield continues to be a major focus of soil research. Stabilization of SOM is the major mechanism upon which physical, chemical, and biological mechanisms stabilize and therefore, sustain biomass productivity (Lal 2006; 2010a;b). Soil management techniques that focus on providing immediate nutrients for crop production have little long-term impact on SOM, while those that provide recalcitrant amendments improve SOM (Palm et al. 2001). Although SOM stability plays an important role in restoring crop yield, nutrient release through decomposition is the main mechanism for short-term improvements in crop yield (Kimetu et al. 2008).

Biochar recalcitrance does not allow for nutrient release through decomposition to be the dominant factor causing changes in crop yield. As shown in Table 2, mechanisms attributed to biochar's impact on crop yield, especially in degraded soils of the tropics, are generally chemically and biologically related and include increased nutrient retention due to changes in CEC, increased soil pH from release of carbonates, and improved habitat for soil biota (Glaser et al. 2002; Thies and Rillig 2009). Nutrient retention by absorption, increased AWC due to changes in porosity, and reduced soil strength are the main physical mechanisms in which biochar improves crop yield. Additionally, the 'charcoal effect', discussed below, may also play an important role in improving crop yield (Graber et al. 2010). Biochar induced immobilization of N is a major mechanism of observed crop yield declines.

Asai et al. (2009) measured leaf chlorophyll concentration (SPAD-values) and grain yield of two rice cultivars under biochar application with both N and P fertilizers. Grain yield increased with 4 and 8 Mg ha^{-1} of biochar application. At 16 Mg ha^{-1}, grain yield decreased, probably resulting from increased N deficiencies caused by biochar, which has a high C:N ratio. Immobilization of N can be a major limiting factor to enhanced agricultural production (Saito 2006). Yet, a lysimetric study indicated that bagasse biochar is effective in reducing NO_3-N concentrations in percolating water and increasing N absorption by sugarcane (Chen et al. 2010).

Brockhoff (2010) observed trends of increasing AWC, decreasing ρ_b, K_s, and rooting depth for turf grass ('T-1' creeping bentgrass) in sand with increasing biochar treatment rates. Shallower roots could have been from anaerobic conditions associated with biochar AWC and/or lack of limiting factors with increasing biochar amendment, allowing plants to survive without sending roots deeper. In a greenhouse study, fertigated pepper (*Capsiccum annum* L.) and tomato (*Lycopersicum esculentum* Mill.) plants in wood-derived biochar and coconut (*Cocos nucifera* L.) fiber:tuff growing medium provided insight into the 'charcoal effect' on plant productivity (Graber et al. 2010). Improved plant growth, evident in tomato plant height and leaf area and pepper plant leaf nodes and leaf area, was attributed to one of two mechanisms related to the "charcoal effect:" (i) a shift to more beneficial microbial communities was caused by residual organic tars or (ii) low concentrations of chemicals in biochar stimulated a plant immune response inducing more aggressive growth.

Table 2. Crop yield response to biochar amendment and attributed mechanisms.

Soil and Conditions	Biochar Description ($Mg\ ha^{-1}$)	Crop	Response	Mechanisms	Comments	References
Loamy sand Field plot	Charcoal soil site (CSS) Adjacent field site (AFS)	Maize (*Zea Mays*)	GY up 91% and 276% over control = 78% Cob weight 32%	Exchangeable cations and nutrient availability		Oguntunde et al. 2004
Ferrosol Calcarosol Greenhouse	2 types of papermill sludge 0 – 10 $Mg\ ha^{-1}$ < 2mm size	Wheat (*Triticum astivum*) Soybean (*Glycine Max*) Radish (*Raphanus sativus*)	Crop + ferrosol = increased TDW Calcarosol without fertilizer resulted in no change for soybean, declines in wheat, and increases in radish;	pH increase, nutrient retention through adsorption	Earthworms prefer biochar in Ferrosol; no preference in Calcarosol may indicate a pH preference	Van Zwieten 2010
Acidic alfisol Greenhouse	Greenwaste mixture 0 – 100 $Mg\ ha^{-1}$	Radish	Up to 266% increase DM with N fertilizer, no significant change without fertlizer	Reduced soil strength, pH increase, increased FC moisture content	10 $Mg\ ha^{-1}$ had significant negative effects	Chan et al. 2007
Oxisol 4 year field	Wood commercial cooking biochar 0 – 20 $Mg\ ha^{-1}$ < 5 mm	Maize	Control declined 4th year by over 50% while biochar related yield 71% and 140% above control	pH increase (reduced Al^{3+} availability) and nutrient retention		Major 2010
Sandy clay loam Greenhouse	Oil mallee 0 – 6 $Mg\ ha^{-1}$ < 2-3 mm	Wheat	Biochar with mineral fertilizer significantly increased GY, G H^{-1}, and GW compared to biochar with soluble fertilizer	AWC during drought, SOM increase at 6 $Mg\ ha^{-1}$, AM fungal colonization.	Mycorrhizal fungi improved water supply	Solaiman 2010
Sandy clay loam Sand Clay loam Field plots	Eucalyptus wood 0 – 3.3 $Mg\ ha^{-1}$	Wheat	Up to 40% GY increase reveals fertilizer efficiency, 5 % decrease on clay loam soil	Reduced surface albedo (- water effect), fertilizer efficiency (P uptake),	Reduced tiller loss with biochar amendment	Blackwell 2010
Loamy sand Kandiudult Field plots	Peanut (*Arachis hypogaea*)hull and mixed pine chip 0 – 22.4 $Mg\ ha^{-1}$ < 2.8 mm	Maize	GY and stover tended to decrease with increasing biochar, even with fertilizer. First season declines from pine chip biochar were not observed during the second season.	Short-term increase of base cations, soil pH (pine chip decreased pH)	Concluded biochar as useful for C sequestration	Gaskin et al. 2010

GY = grain yield, DM = dry matter, TDW = total dry weight, FC = field capacity, AWC = plant available water capacity, SOM = soil organic matter

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Two poultry litter biochars produced at different temperatures and mixed with an Alfisol had significant impact on total dry matter (TDM) of radish plants (Chan et al. 2008). A 320% increase in TDM was observed for the 50 Mg ha^{-1} with N fertilizer compared to the control without fertilizer. Reduced soil strength, earthworm preference and change in microbial biomass C (MBC) indicated an underlying mechanism other than the liming effect and nutrient retention and could have been the charcoal effect referred to by Graber et al. (2010).

Summary and Proposal

Biochar has potential to improve physical characteristics of agricultural soils. It can increase crop yield, while providing ancillary benefits such as reducing chemical fertilizer use and improving soil biota interactions. Potential research opportunities exist regarding the impact of biochar on temperate soils (Atkinson et al. 2010), especially focused on biochar stability, incorporation method, application rate, and fertilizer efficiency (Glaser et al. 2002; FFTC 2007).

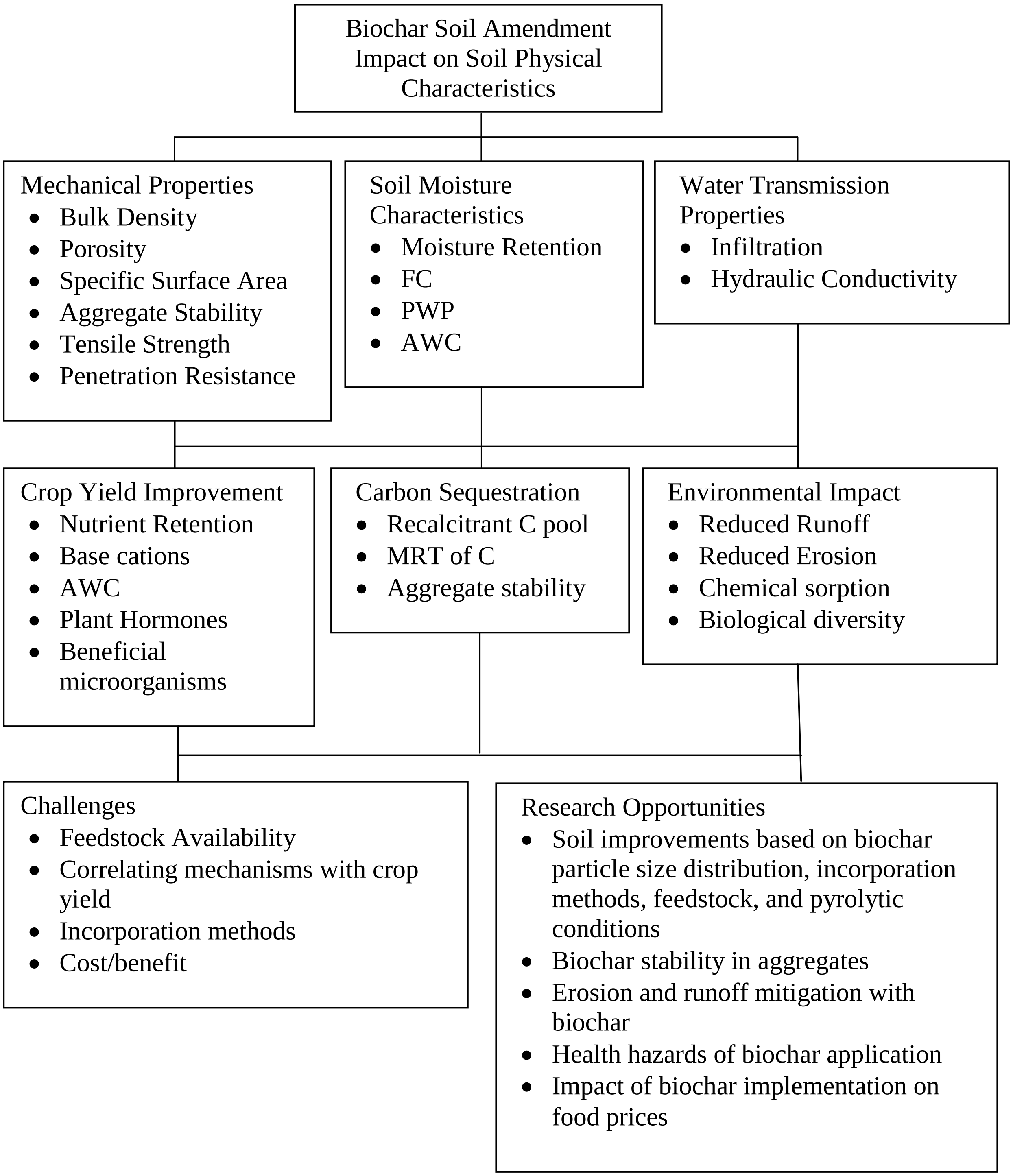

Figure 1. Soil physical properties and processes managed with biochar amendment.

In view of the need for field scale experiments on biochar, a field study was designed to initiate a long-term experiment on 1.5 ha of a central Ohio Alfisol (Aeric Ochraqualfs). The experiment focuses on biochar application rate and fertilizer rate in a conventional corn-soybean rotation. This study focused on the impact of biochar on the soil physical characteristics and crop yield. Research was guided by the following objectives

1) To examine the mechanical properties of biochar amended soil and biochar itself.
2) To evaluate the immediate impact of biochar amendment on water infiltration rate.
3) To evaluate moisture retention characteristics of a biochar amended soil.
4) To correlate soil physical properties with crop yield.

These objectives reflect the predictions and hypotheses described herein. The principal hypotheses are: (i) soil ρ_b will decrease, and, consequently, f_t will increase with biochar amendment because of the physical structure of biochar, (ii) soil tensile strength, penetration resistance, and aggregate stability will remain unchanged with biochar amendment because biochar does not provide labile C to strengthen aggregates, (iii) tillage to incorporate biochar will also decrease soil ρ_b and increase f_t, but will decrease TS, penetration resistance, and aggregate stability, from physical disturbance leading to additional aeration and surface exposure to rain drops, (iv) biochar amendment will improve water retention by increasing retention and residual pore volume, (v) additional macropores from biochar amendment and tillage will increase K_s and water infiltration of the clay loam soil.

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Chapter 2: Mechanical properties of biochar amended soil

Abstract

Soil amended with biochar has important implications regarding agricultural and environmental sustainability, specifically agronomic productivity, and carbon (C) sequestration. Thus, a field experiment was conducted on a Crosby soil in central Ohio to assess the impact of biochar incorporation on corn (*Zea mays*)-soybean (*Glycine max L.*) system. Three biochar rates were replicated 12 times: 0 Mg ha^{-1} (TC), 5 Mg ha^{-1} (TB5), and 25 Mg ha^{-1} (TB25). Area around plots, managed with no-till practices for 5 years, acted as a no-till control (NTC). Changes in soil physical characteristics resulted from incorporating a woodchip biochar up to 12 cm beneath the soil surface using a rotovator. The impact of freeze and thaw cycles (FTCs) on biochar stability resulted in a maximum decrease of 59% in tensile strength, and a biochar particle size distribution shift from 55% < 2 mm to 47% < 2 mm after 9 cycles. Soil bulk density (ρ_b) of TB25 and TC of the surface depth (0 – 10 cm) were 1.28 g cm^{-3} and 1.41 g cm^{-3}, respectively, and significantly lower than that of the NTC of 1.57 g cm^{-3}. No significant differences were observed in ρ_b of the deeper layer. There occurred a significant increase in macro-pores (transmission pores) and micro-pores (retention pores). Tillage had a significant impact on penetration resistance as evident by declines of 58%, 70%, 59%, and 18% at 2 cm, 4.5 cm, 7 cm, and 12 cm depths, respectively, as compared to NTC. Tillage had a significant negative impact on aggregate stability, while biochar amendment did not.

1. Introduction

The strong need for field scale research in regards to agronomic benefits of biochar soil amendment, especially in temperate climates, is widely recognized (Glaser 2007; Atkinson et al. 2010; Jha et al. 2011). Production of biochar provides hydrocarbons to offset fossil fuel use (Mathews 2008), while application to soil improves quality and crop yield and provides ancillary benefits (Lehmann et al. 2006; McHenry 2009). As an effective soil conditioner, it typically improves nutrient retention and increases pH, which leads to increase in crop yields in highly degraded tropical soils (Glaser et al. 2002; Lehmann et al. 2003; Major et al. 2010). Soils of arid environments benefit from biochar amendment through increased moisture retention and fertilizer use efficiency, which reduces drought stress at critical stages (Blackwell et al. 2010; Solaiman et al. 2010; Van Zwieten et al. 2010). Research on Ultisols in southeastern United States has shown limited success in increasing crop yield using biochar (Gaskin et al. 2010). In contrast, greenhouse experiments show drastic improvements in plant growth attributed to high water and nutrient use efficiencies with biochar amendment (Uzoma et al. 2011). Increased crop yield is generally attributed to increased moisture retention and pH, since liming of acidic soils reduces aluminum toxicity (Sombroek 2003; Chan et al. 2007; Major et al. 2010).

Improving soil physical properties can reduce the risks of degradation of agricultural soils caused by traditional management techniques such as tillage. Biochar can alleviate soil compaction by decreasing bulk density, which increases porosity and accentuates favorable soil processes (Laird et al. 2010). Application of biochar asa soil amendment reduces tensile strength and penetration resistance (Chan et al 2007; 2008; Busscher et al. 2009). In addition to improved soil mechanical properties, it also increases water infiltration rate, reduces runoff, and decreases erosion (Ayodele et al. 2009; Asai et al. 2009). Biochar reduces saturated hydraulic conductivity (K_s) in coarse-textured soils used for turfgrass (Brockhoff et al. 2010), and increases K_s in heavy-textured soils by improving macropores. There are also improvements in water retention characteristics including available water capacity (AWC) and field capacity (FC) (Lehmann et al. 2003; Chan et al. 2007; Asai et al. 2009; Chen et al. 2010; Laird et al. 2010; Jones et al. 2010; Brockhoff et al. 2010). Production of biochar and subsequent occlusion in soil aggregates enhances C sequestration (Lehmann 2009, Brodowski et al. 2006).

Therefore, the aim of this study was to assess the impact of biochar incorporation in a soil used for cultivation of a typical Midwestern U.S. corn/soybean rotation. The specific objective is to determine changes in soil physical properties, and crop yield as a result of biochar amendment. The hypotheses, with respect to biochar amendment, are (i) bulk density is decreased and porosity is increased, (ii) water stable aggregates decrease with tillage and not affected by biochar amendment since no labile C is gained in the soil, (iii) moisture retention and water infiltration rate increase with biochar amendment due to an increase in total porosity, (iv) crop yield may increase with biochar amendment, because of increased AWC.

2. Materials and methods

2.1 Location and design

The field experiment was established in early Spring of 2010 at the Waterman Farm of The Ohio State University in Columbus, OH (40°00'N, 83°02'W) on a Crosby silt loam soil (fine, mixed mesic Aeric Ochraqualf) (Soil Web Survey, 2009). Average temperature for 2010 was 12.0 °C, which is 0.6 °C above the historical average. Total annual precipitation was 80.54 cm, of which 46.2 cm occurred between the frost-free period of April 28th and October 22nd. The 1.4–ha site has been conventionally managed for corn and soybean rotations for the previous 4 years. Treatments were laid out according to a randomized complete block design involving a total of 36 plots (4.33 m by 6.2 m with 2 m buffers). Each block contains all combinations of treatments including a one-time biochar application at 3 rates(0, 5, or 25 Mg ha^{-1}) and mineral fertilizer application at 2 rates (75 kg ha^{-1} or 150 kg ha^{-1}) only to the corn crop. Each block was replicated 6 times across the center of the site. At both ends of the site outside of the plots is 0.4 ha of cultivated land under no-till management without biochar amendment.

In April 2010, randomly assigned plots received 14 kg or 70 kg of biochar applied by hand and incorporated by rotovator to approximately 12 cm depth. Control plots (TC) were also tilled with the rotovator to determine the effect of tillage on measured soil physical parameters. Soybean was planted as the first crop and, since fertilizer was not applied, there were 12 replicates of each treatment during the first growing season. With so many replicates, it was unnecessary to take samples from every plot in order to quantify the impact of biochar incorporation on soil physical parameters.

2.2 Biochar characterization

Biochar, obtained from a commercial charcoal producer, was pyrolyzed at 425 °C from Oak (*Quercus* ssp.) wood chips in a Missouri kiln. Particle size distribution of biochar was determined by dry-sieving with a nested stack of sieves for 15 minutes. Bulk density (ρ_b) of biochar was estimated by directly measuring dry mass and volume of 5 replicates of bulk samples. Volume was estimated using Archimedes' principle with water displacement measured in a graduated cylinder.

2.3 Freeze-thaw study

The impact of freeze-thaw cycles (FTCs) on particle size distribution of biochar was estimated under saturated conditions to determine the maximum rate of physical degradation of biochar. Treatment (0, 3, 6, and 9 FTCs) included approximately 75 g of biochar replicated 3 times. Each replicate was placed in individual zip-lock bags, filled with water, and sealed. Occasional shaking of the samples ensured a complete saturation of all samples. Each FTC included 48 hours in a – 20 °C freezer and 48 hours at room temperature (23 °C). The control (BO) remained saturated at room temperature during all FTCs. As each treatment finished FTCs, the contents of the bag were carefully washed into a beaker and oven-dried at 105 °C. Samples were dry-sieved on a nested stack of sieves for 15 minutes and the contents of each sieve were weighed. Particle size distribution was estimated using the average of three replicates. Tensile strength of biochar particles was determined for BO and 3FTC as described in the following section.

2.4 Tensile strength

Tensile strength (TS) of biochar particles was determined by using a crushing apparatus (Dexter and Kroesbergen 1985). The TS is proportional to the minimum force (F) required to cause rupture of an aggregate and inversely proportional to the square of the average diameter of the particle (Rogowski et al. 1968). Estimated TS was calculated according to eq. 1

$$\mathrm{TS} = 0.567\,\frac{F}{{d_{agg}}^{2}} \quad \text{(Eq 1)}$$

Each particle diameter (d_{agg}) was estimated by using a caliper to measure three widths of different dimensions, which were then averaged. The F was estimated by taking a proportion of the downward force caused by a hanging bucket of water. The proportion was determined as the distance (X_1) from the hanging point of the bucket to the fulcrum divided by the distance (X_2) from the crushing point to the fulcrum. Three treatments were used on biochar particles (2 – 12 mm diameter): air-dry control (BO), saturated control (SBO), and 3 FTCs (BFT3).

2.5 Soil methods and analyses

During water infiltration measurements, a cone penetrometer was used to measure penetration resistance at multiple depths to 17 cm or to the maximum pressure of 1000 kPa (Bradford 1986). Five replicates were measured for each plot for a total of 15 samples per treatment. Soil core samples taken 24 hours after water infiltration measurements were placed in plastic bags in a cooler and taken back to the laboratory. Soil was trimmed from cores, and was used to measure gravimetric moisture content (w) by oven drying at 105 °C. Cores were stored in 3 °C pending analysis. Wet bulk density (ρ_b') was calculated from soil core mass and the volume of 7.5 cm diameter and 7.5 cm long cores. Dry bulk density (ρ_b) and volumetric moisture content (θ) were calculated from w and ρ_b'. Total porosity (f_t) was determined from ρ_b and an assumed 2.65 g cm^{-3} soil particle density. Since sampling was conducted 24 hours after saturation, θ_{FC} represents in-situ field moisture capacity (FC). Available water capacity (θ_{AWC}) was calculated as the difference between θ_{FC} and permanent wilting point (θ_{PWP}), which was measured in the lab as described below.

In the Spring of 2011, soil bulk and core samples were collected from 0 – 10 cm depth, placed in plastic bags in a cooler, and taken back to the laboratory. Soil was trimmed from cores, and was used to measure gravimetric moisture content (w) by oven drying at 105 °C. Cores were stored in 3 °C pending analysis. Bulk samples were air dried and dry-sieved into two fractions (5 – 8 mm and < 2 mm). Wet bulk density (ρ_b') was calculated from soil core mass and the volume of 7.5 cm diameter cores. Dry bulk density (ρ_b) and volumetric moisture content (θ) were calculated from w and ρ_b'. Total porosity (f_t) was determined from ρ_b and an assumed 2.65 g cm^{-3} soil particle density. Since sampling was conducted 24 hours after saturation, θ_{FC} represents in-situ field moisture capacity (FC). Available water capacity (θ_{AWC}) was calculated as the difference between θ_{FC} and permanent wilting point (θ_{PWP}), which was measured in the lab as described below.

2.6 Soil pore size distribution

After 24 hours of saturation, cores were weighed and placed on a tension table. Suction was applied for 24 hours at each level (-1 kPa, -3 kPa, and -6 kPa) at which time the cores were moved to pressure plates for equilibrium of moisture content at -33 kPa, -100 kPa, and -300 kPa (Klute 1986). Samples were weighed when equilibrium was attained (4-6 days), as indicated by no discharge. Soil was dried at 105 °C, and the oven dry weight was determined for each core. Soil was wet sieved through a 2 mm sieve to determine gravel and biochar contents.

Approximately 20 g of the < 2 mm soil fraction from bulk samples was used to determine moisture content at –1500 kPa pressure (1.5 MPa matric potential). The AWC was calculated as the difference between moisture content values at -33 kPa and -1500 kPa matric potentials, and to the previously mentioned field θ_{AWC}.

Soil pore size distribution was determined by correlating pore size (µm) to the volume of water extracted between two matric potentials. Pore size was calculated using equation 2 (Lal and Shukla 2004).

$$r = \frac{0.1478}{h} \qquad \text{(Eq 2)}$$

where, r is the pore size (µm) and h is the suction (cm of H_2O).

2.7 Aggregate stability

Bulk soil was used to determine soil strength against erosional processes. To determine water stable aggregates (WSA), 50 g of the air dry 5 – 8 mm aggregates were placed on the top of a nested stack of sieves (4.75, 2, 1, 0.5, and 0.25 mm openings), pre-wetted for 30 minutes, and wet-sieved for 30 minutes at 30 cycles min^{-1} with oscillation of 1.25 cm. Soil content from each sieve was oven dried at 105 °C for 24 hours. Adjusted for initial moisture, %WSA was calculated for each size fraction ≥ 0.25 mm (Yoder, 1936). Total WSA (TWSA), geometric mean diameter (GMD), mean weight diameter (MWD) and corrected MWD (MWD_c) were calculated (Kemper and Rosenau, 1986) according to equations 3 – 6.

Total WSA = $\sum \%WSA$ ………………………………………………………... (Eq 3)

GMD = $e^{\left\{\frac{\sum m_i \log x_i}{\sum m_i}\right\}}$ ……………………………………………………….. (Eq 4)

MWD = $\sum x_i \times m_i$ ………………………………………………………. (Eq 5)

MWD_c = 0.876 (MWD) – 0.079 ……………………………………………….. (Eq 6)

where, m_i is the mass of aggregates in a size class of average diameter x_i, and calculated using the above described 5 aggregate size ranges.

2.8 Statistical Analysis

Analysis of data pertaining to soil physical properties was conducted using the PROC GLM procedure in Statistical Analysis Software 9.2 (SAS Institute, 2008). Initial sampling conducted in the fall of 2010 consisted of ρ_b, f_t, pore size distribution, and penetration resistance . Measurements were grouped based on treatment: TB25, TB5 and TC, which are represented by 1 replicate from 3 plots for a total of 3 samples per depth. The NTC represents 3 samples per depth from the NT managed area outside of plots. Additional sampling conducted in the spring of 2011 consisted of ρ_b, f_t, pore size distribution, and aggregate stability. These samples were grouped based on treatment and are all from the 0 – 10 cm depth. Treatments TB25 and TC are represented by 3 replicates from 6 plots for a total of 18 samples. No-till control (NTC) represents 6 samples from the no-till managed area outside of plots. All data in tables are reported as least square means of the treatment. Least significant difference (LSD) values were calculated for each depth and parameter. Unbalanced data from spring 2011 samples required Tukey-Kramer adjustment for multiple comparisons to determine statistical significant differences. Least significant difference (LSD) values were calculated using the number of NTC samples so as to attain the most conservative values.

3. Results and discussion

3.1 Biochar characterization

The biochar used in this study has a mean ρ_b of 0.58 Mg m^{-3} as compared to the mean soil ρ_b of 1.48 Mg m^{-3}, which suggests that the biochar amendment will decrease ρ_b and increase f_t (Brockhoff et al. 2010). Evident in Table 3, biochar TS is not influenced by moisture content, but 3 FTCs weaken biochar particles by 51%, 56% and 59% as compared to saturated large, medium and small particles, respectively. On average across all treatments, medium particles have 8.5% and 18.2% lower TS than respective large and small particles. This trend suggests that as biochar particles become smaller there are fewer planes of failure, which may delay the breakdown of particles below the 2 mm size in which soil constituents are classified (Lal and Shukla 2004).

Table 3. Mean TS (kPa) of 3 class sizes of biochar particles.

Treatment	Tensile Strength (kPa)		
	Large (> 8 mm)	Medium (5 – 8 mm)	Small (2 – 5 mm)
BO	1.11a	1.05a	1.25a
SBO	1.21a	1.05a	1.28a
BF3	0.62b	0.59b	0.76b
$LSD_{0.05}$	0.35	0.34	0.35

Significant difference ($p < 0.05$) indicated by different letters was attained by Tukey-Kramer adjustment for multiple comparisons. BO = original biochar; SBO = saturated biochar; BF3 = saturated biochar impacted by 3 freeze/thaw cycles.

Figure 2 displays particle size distribution of biochar indicating that > 95% of the original biochar (BO) is ≥ 2 mm in diameter. After 3 FTCs, approximately 90% of the biochar is ≥ 2 mm, and by 9 FTCs, 53% of the biochar is ≥ 2 mm. Soils that experience regular FTCs will break down larger particles, which may increase pore space and surface area accessible by moisture and air (Othman et al. 1994). Evidence suggests the interior of large particles is accessed by moisture and nutrients (Dunisch et al. 2007), while other studies suggest biochar particle size plays a limited role in crop growth (Lehmann et al. 2003).

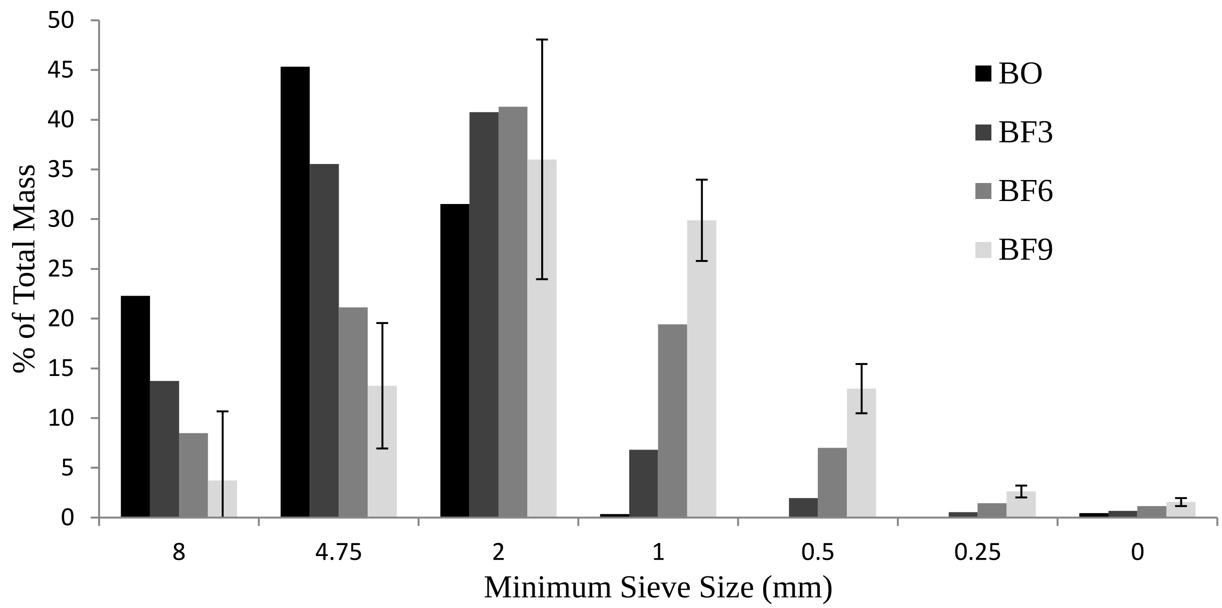

Figure 2. Impact of FTCs on the particle size distribution of biochar. BO = original biochar, BF3 = saturated biochar impacted by3 FTCs, BF6 = saturated biochar impacted by 6 FTCs, BF9 = saturated biochar impacted by 9 FTCs.

In general, studies on FTCs have a short freeze period (1 day) and a long thaw period (6 days), but this is mainly to allow for biological processes to equilibrate. For example, a decline in free lipids, a labile form of soil organic matter (SOM), with increasing FTCs was attributed to a shift in microbial communities associated with competition for the substrate (Feng et al. 2007). Bound lipids and lignin compounds, stable forms of SOM, did not change with increasing FTCs. This trend suggests that chemical changes in stable SOM fractions are limited in soils experiencing FTCs. The rapid increase in biochar particles < 2 mm with increasing FTCs warrants additional research to determine chemical and biological processes impacting biochar.

Wet-sieving soil samples after analysis to quantify biochar concentration for each sample resulted in 0.002 g g^{-1} and 0.021 g g^{-1} for TB5 and TB25 treatments, respectively. These concentrations are equivalent to 2.7 Mg ha^{-1} and 28 Mg ha^{-1} effective biochar application rates based on the average ρ_b of TC soil (Table 3) tilled to a depth of 10 cm.

3.2 Soil bulk density and total porosity

The tillage effect on soil ρ_b and f_t was significant (Table 4) only in the 0 – 10 cm depth. Air porosity (f_a) improved significantly with tillage, but biochar amendment limited this improvement (Table 4). The improvement in moisture content at θ_{FC} and w_{FC} observed in TB25 over TB5 and TC suggests biochar enhances soil moisture retention. This trend is not observed in subsequent depths confirming that biochar was not incorporated below 10 cm (Table 4).

Table 4. Soil physical properties and water flow of samples at field capacity.

Depth	Treatment	w_{FC} (g g^{-1})	ρb (g cm^{-3})	θ_{FC} (cm^3 cm^{-3})	f_t (cm^3 cm^{-3})	f_a (cm^3 cm^{-3})
0 – 10 cm						
	TB25	0.30a	1.28b	0.38a	0.51a	0.13ab
	TB5	0.24b	1.40b	0.33b	0.47a	0.14ab
	TC	0.24b	1.33b	0.32b	0.49a	0.17a
	NTC	0.22b	1.57a	0.35ab	0.40b	0.05b
	$LSD_{0.05}$	0.02	0.15	0.04	0.06	0.09
10 – 20 cm						
	TB25	0.21a	1.51a	0.32a	0.43a	0.10a
	TB5	0.19a	1.54a	0.30a	0.42a	0.12a
	TC	0.20a	1.56a	0.31a	0.41a	0.10a
	NTC	0.21a	1.52a	0.32a	0.42a	0.10a
	$LSD_{0.05}$	0.03	0.11	0.03	0.04	0.04
20 – 30 cm						
	TB25	0.20a	1.51a	0.30a	0.43a	0.12a
	TB5	0.20a	1.60a	0.33a	0.39b	0.06b
	TC	0.20a	1.55a	0.31a	0.41ab	0.10ab
	NTC	0.21a	1.55a	0.33a	0.41ab	0.07ab
	$LSD_{0.05}$	0.04	0.09	0.05	0.03	0.05

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = NT managed area adjacent to plots. Significant difference ($p < 0.05$) indicated by different letters.

Additional sampling of TB25, TC, and NTC treatments of the 0 – 10 cm depth in the spring of 2011 provided further insight into the effects of biochar incorporation . As a result of biochar incorporation, soil ρ_b in TB25 decreased by 7.8% and 12.5%, while f_t increased by 6.4% and 16.3% for TC and NTC, respectively (Table 5). At 25 Mg ha^{-1}, biochar increased w by 12.5% and 35% and θ by 7.1% and 16.2% over TC and NTC, respectively. These increases in moisture content are similar to those reported by Laird et al. (2010) and Chan et al. (2009). Field measurement of θ_{FC} and θ_{AWC} resulted in TB25 with the highest values, although lack of significant difference in θ_{PWP} between TB25, TC, and NTC may be attributed to the lack of biochar in the < 2 mm size fraction, as is evident in Figure 1.

Table 5. Soil physical properties from spring 2011 samples taken at field capacity (FC).

Treatment	w ($g\ g^{-1}$)	ρb ($g\ cm^{-3}$)	θ_{FC} ($cm^3\ cm^{-3}$)	θ_{PWP} ($cm^3\ cm^{-3}$)	AWC ($cm^3\ cm^{-3}$)	f_t ($cm^3\ cm^{-3}$)	f_a ($cm^3\ cm^{-3}$)
TB25	0.27a	1.33c	0.45a	0.15a	0.31a	0.50a	0.05a
TC	0.24b	1.41b	0.42b	0.14a	0.28b	0.47b	0.05a
NTC	0.20c	1.52a	0.37c	0.14a	0.22c	0.43c	0.06a
$LSD_{0.05}$	0.015	0.08	0.035	0.01	0.03	0.03	0.05

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = NT managed area adjacent to plots. Significant difference ($p < 0.05$) indicated by different letters attained by Tukey-Kramer adjustment for multiple comparisons.

The data in Table 5 suggest that biochar amendement at the 25 Mg ha^{-1} rate has a similar impact on soil physical properties as tillage. Both tillage and biochar amendment result in increased porosity. However, tillage must be implemented consistently to maintain macro-pore space (Carter 1988) , while biochar TS lends itself to a long-term stability in which pore space is maintained, unless clogged by primary particles and organic matter (OM) (Kwon and Pignatello 2005). If pore space is clogged by OM, decomposition by soil microbes may lead to reopening of pore space (Zackrisson et al. 1996). Further study on the dynamics of soil and biochar porosity is necessary (Hammes and Schmidt 2009).

3.3 Pore size distribution

Tillage had measureable impacts on soil pore size distribution (Figure 3). In the 0 – 10 cm depth, significant ($p = 0.05$) increases in TC over NTC were observed in the volume of pores with equivalent cylindrical diameter (ECD) of 1500 µm and 150 µm (Figure 3). Pores of these ECDs are classified as transmission pores which provide rapid percolation of water (Greenland 1977). No other significant differences were observed across treatments in either the 10 – 20 cm depth or in the 20 – 30 cm depth.

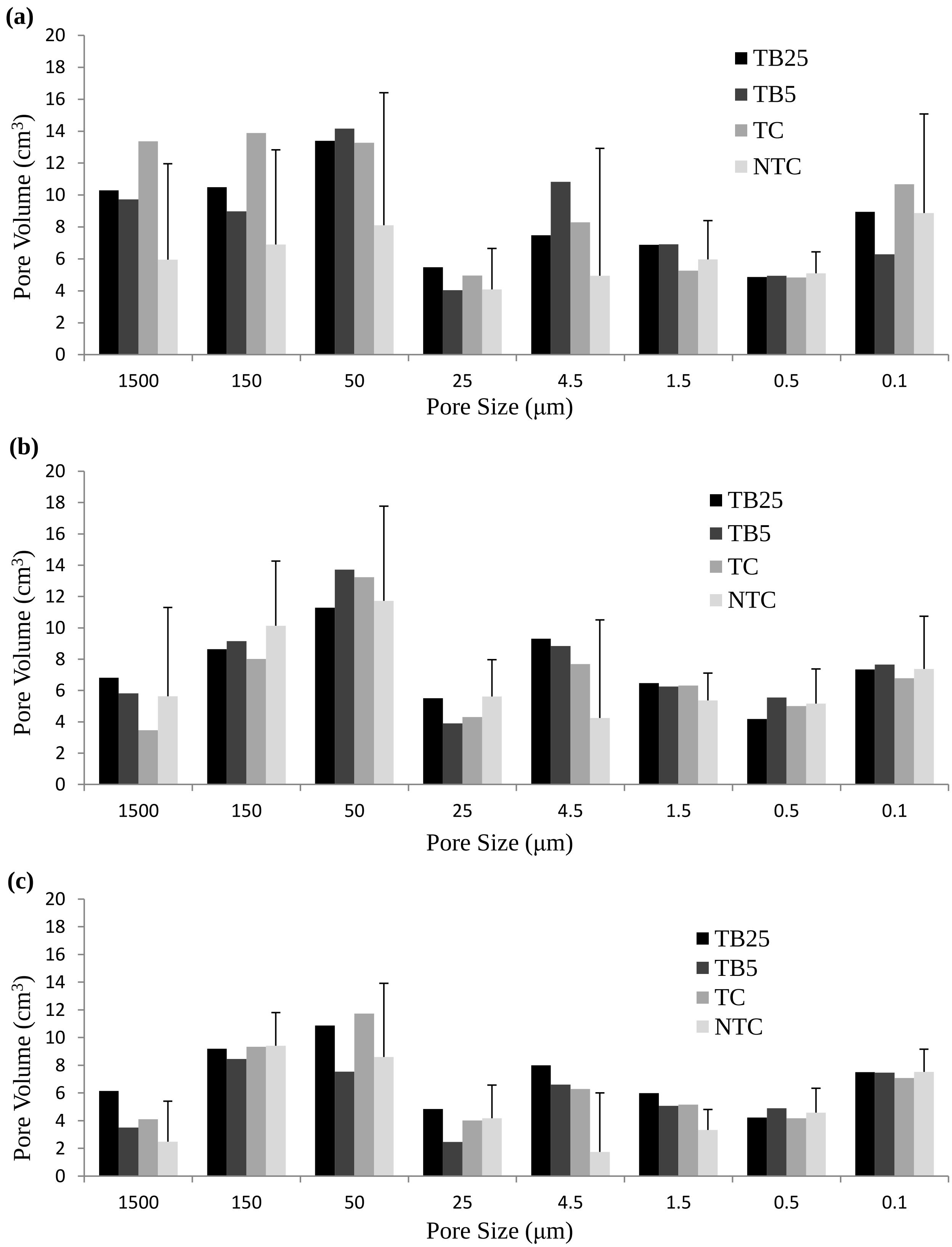

Figure 3. Pore size distribution calculated from moisture retention data for 3 depths: (a) 0 – 10 cm, (b) 10 – 20 cm, and (c) 20 – 30 cm. Error bars are LSD value (p = 0.05) for each pore size.

Additional sampling of TB25, TC, and NTC treatments of the 0 – 10 cm depth in the spring of 2011 provided further insight into the effects of biochar incorporation. Tillage has measureable impacts on pore size distribution (Figure 3). The greatest impact was observed in the volume of pores with ECD of 1500 µm, 50 µm, and 0.5 µm. The TB25 increase in volume of 1500 µm pores above TC suggeststhat incorporation of biochar enhances macro-pores related to water transmission, while also enhancing moisture retention by increasing the volume of 0.5 µm pores. These data indicate that tillage improves water infiltration and aeration in agricultural soils with low macro-porosity (Carter 1988).

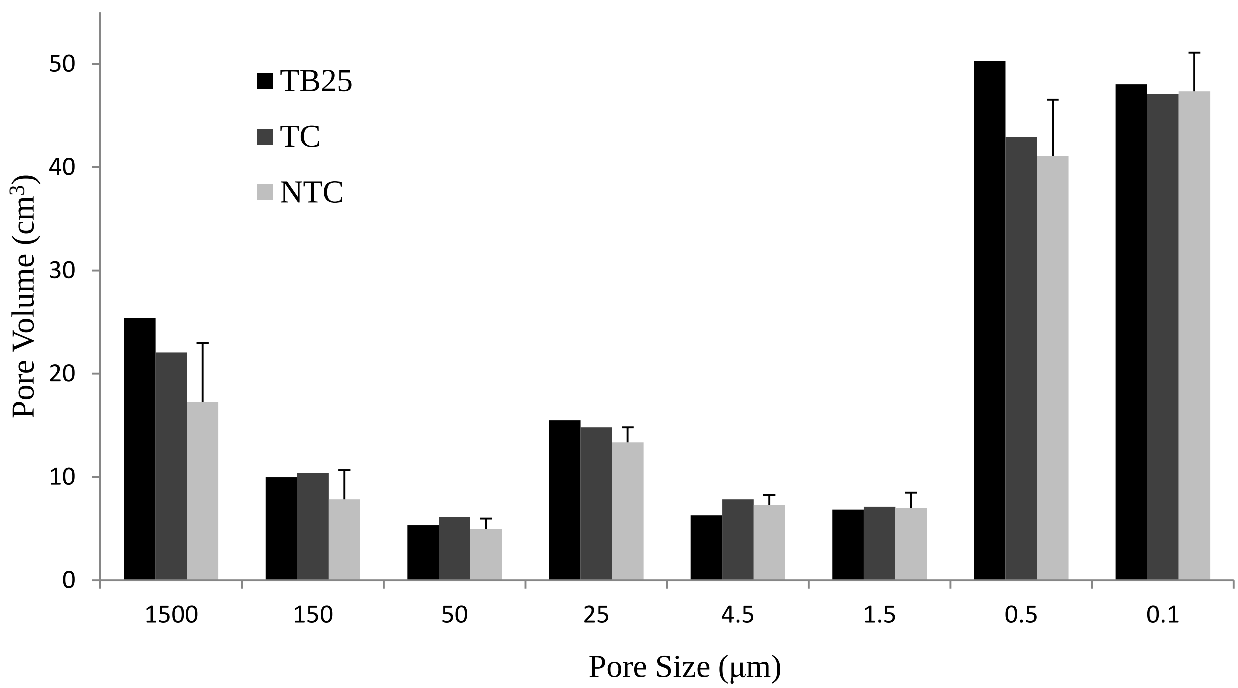

Figure 4. Pore size distribution of the 0 – 10 cm depth. Error bars are LSD value ($p = 0.05$) for each pore size. TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = no-till managed area adjacent to plots.

Significant increases in pore volume were observed in the 1500 and 0.5 µm pore sizes in TB25 over NTC, but not TC. The volume of 0.5 µm pores as a result of biochar amendment increased

17.1% and 22.4% over TC and NTC, respectively. Biochar amendment increases, albeit very little, the 25 µm pore size over NTC. The decrease in volume in 4.5 µm pore size is statistically significant and suggests that biochar lacks pores of 4.5 µm ECD. The small, but statistically significant, increase in pore volume of TC 50 µm pore size suggests that biochar has few pores of this size. This increase suggests that biochar can enhance the pore size distribution of compacted agricultural soils, although much research can be conducted on biochar characterization and soil type.

3.4 Aggregate Stability

Total water stable aggregates (TWSA) decreased with tillage and even further with biochar amendment (Table 6). Tillage induced disturbance is the main cause of differences. Aggregation is a long-term process and requires labile C inputs to the soil, typically from plant roots and soil biota. One growing season is too short a time period to observe recovery in aggregate stability after a soil has been tilled.

Table 6. Mean percent of mass retained from wet-sieving of soil aggregates.

Treatment	Smallest Size of sieve opening (mm)					TWSA (%)	GMD (mm)	MWD (mm)	MWDc (mm)
	4.75 (%)	2 (%)	1 (%)	0.5 (%)	0.25 (%)				
TB25	14.9a	4.8a	5.8b	11.3a*	13.6b	50.3b	1.19a	1.34a	1.09a
TC	13.4a	5.7a	7.2a	13.7a	15.5ab	55.3ab	1.13a	1.31a	1.07a
NTC	17.5a	6.1a	8.1a	14.8a	18.0a	64.5a	1.15a	1.62a	1.34a
LSD	7.1	1.4	1.2	3.5	2.9	7.7	0.12	0.43	0.37

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = no-till managed area adjacent to plots. Significant difference ($p < 0.05$) indicated by different letters were attained by Tukey-Kramer adjustment for multiple comparison. Significant difference from TC at $p < 0.10$ level is indicated by *.

3.5 Penetration resistance (PR)

Application of biochar did not significantly impact soil PR (Figure 5). In contrast, there were significant differences in PR among tillage treatments. Tillage reduced PR by 58%, 70%, 59%, and 18% at 2 cm, 4.5 cm, 7 cm, and 12 cm depths, respectively. The reduction in PR at 12-cm depth may be under-estimated due to the maximum measured PR of 1000 kPa. Thus, the small, but significant difference in PR measurements suggests that tillage had a significant effect on PR to 12-cm depth.

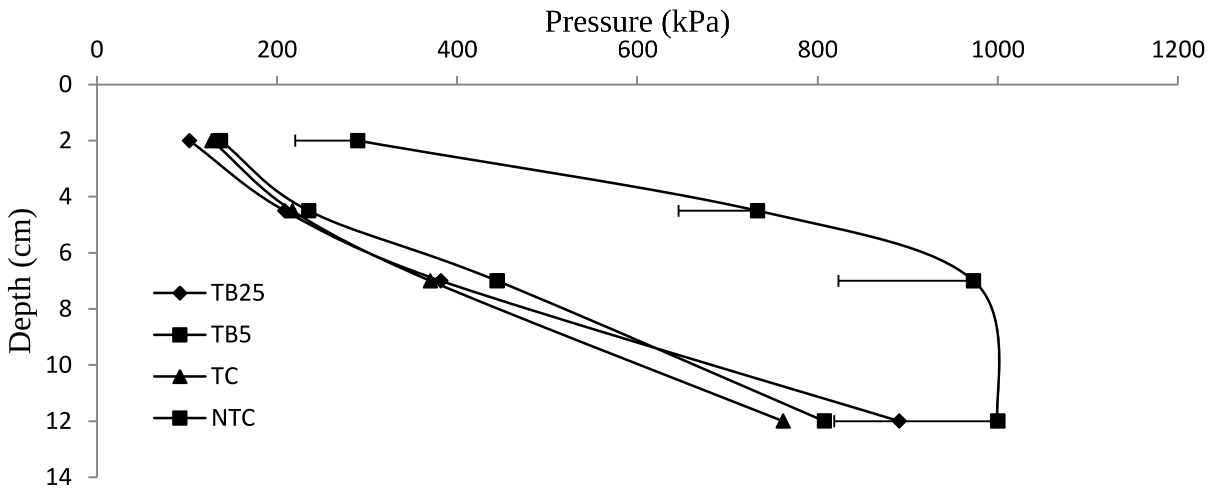

Figure 5. Penetration resistance (kPa) was measured at 4 depths for each treatment. Horizontal bars are lsd values ($p = 0.05$) for each depth measurement. TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = no-till managed area adjacent to plots.

4. Conclusion

Biochar altered pore size distribution, improved soil structure, and enhanced moisture characteristics. Reduction in soil bulk density and increase in total porosity suggests biochar application to soil at 25 Mg ha^{-1} can be a more effective long-term management compared to tillage. Data from pore size distribution suggests biochar incorporation into soil results in favorable soil physical conditions conducive to both transmitting and retaining water. Additionally, freeze/thaw cycles have a significant impact on biochar particle size distribution and tensile strength, which suggests that enhancements of soil mechanical properties might improve with each successive season. Tillage had a significant impact on penetration resistance, while biochar amendment did not. Yet, a more accurate and practical alternative to determine the impact of biochar soil amendment on plant root development would be to measure below-ground biomass and biochar concentration in the root zone. Opportunities for long-term research exist in continuing to monitor changes in soil mechanical properties. Specifically, changes in pore size distribution and aggregate stability over time can provide insight into changing soil moisture dynamics.

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Chapter 3: Hydrological properties and crop yield of biochar amended soil

Abstract

Incorporation of biochar into soil provides a wide range of benefits from agricultural sustainability to carbon (C) sequestration. Thus, a field experiment was conducted to assess the impact of biochar incorporation and soil cultivated to corn (*Zea mays*)-soybean (*Glycine max L.*) rotation. Three biochar rates were replicated 12 times: 0 Mg ha^{-1} (TC), 5 Mg ha^{-1} (TB5), and 25 Mg ha^{-1} (TB25). Area adjacent to plots, managed with no-till (NT) practices for 5 years, acted as a NT control (NTC). Biochar was incorporated to 12 cm soil depth using a rotovator. At the end of the first season, field measurements consisted of 3 replications of water infiltration and core sampling to three depths (0 – 10 cm, 10 – 20 cm, and 20 – 30 cm) for moisture characteristic analysis. Soybean was harvested in the fall of 2010 and soil samples were taken in the spring of 2011. Additional sampling in the spring of 2011 provided further insight into moisture characteristics impacted by biochar amendment in the surface depth. The soil moisture characteristic curve for TB25 was consistently higher across all soil moisture potentials, with the exception of – 1500 kPa, but significantly different only at saturation. Available water capacity (AWC) of TB25 was 9.6% and 29% more than TC and NTC, respectively. Saturated hydraulic conductivity (K_s) of TB25 increased 33% and 78% over TC and NTC, respectively. Water infiltration measurements resulted in no significant differences among treatments, as tillage likely caused significant variance. Compared to TC, TB25 and TB5 soybean above-ground biomass improved 1100 kg ha^{-1} and 600 kg ha^{-1}, respectively, while grain yield improved 347 kg

ha^{-1} and 350 kg ha^{-1}. Significant correlations were observed between biochar concentration, physical properties, and soybean above-ground biomass and grain yield.

1. Introduction

Soil structure is characterized by pore characteristics since soil processes are directly influenced by them. Surface run-off and soil erosion are examples of processes impacted by soil pore structure. Principal properties affected by the pore structure include, but are not limited to, water infiltration and available water capacity (AWC). Macro-pores (> 50 µm) are classified as transmission pores (Greenland 1977), which can be influenced by the relationship between soil management and the response of soil biota, especially earthworms (*Lumbricus rubellus*). Tilled agricultural soils can enhance macro-pore structure in the short term, but over time hard pans develop below the tilled soil through which water transmission is limited. Pore continuity and distribution throughout the soil profile is severely disrupted by tillage reducing the infiltration rate (Kutilek 2004). Decreased water transmission leads to increased surface run-off, erosion, and ground water depletion. Several management techniques remediate this effect including NT or conservation tillage practices, cover cropping, and mulching. In general, practices that decrease soil disturbance and increase soil organic carbon (SOC) tend to improve soil pore structure (Abid and Lal 2009).

Biochar soil amendment can be a sustainable agricultural practice in which enhanced plant AWC, nutrient retention, and changes in soil pH lead to increased crop growth while sequestering C (Glaser 2007; Lehmann 2006). Biochar can alleviate soil compaction by decreasing bulk density (Laird et al. 2010), which increases pore space and improves infiltration and hydraulic conductivity. Responses by moisture characteristics, including AWC and field capacity (FC), depend on the type of biochar, soil type, and incorporation method (Asai et al.

2009; Chen et al. 2010; Laird et al. 2010; Jones et al. 2010; Brockhoff et al. 2010). Biochar reduces saturated hydraulic conductivity (K_s) in sandy soil used for turfgrass (Brockhoff et al. 2010), and increases K_s in heavy-textured soils by increasing macropores. In addition to improved soil moisture retention, biochar amendment increases water infiltration rate which reduces erosion caused by surface run-off (Ayodele et al. 2009; Asai et al. 2009).

Thus, the objective of this study was to assess the impact of biochar application on soil hydrological properties and crop response. Specific objectives were to determine changes in water infiltration rate and hydraulic conductivity (K_s). The two main hypotheses are (i) moisture retention and water infiltration increase with biochar amendment due to increased total porosity, and (ii) crop yield increases as a result in improved soil physical characteristics.

2. Materials and methods

2.1 Location and design

The field experiment was established in early Spring of 2010 at the Waterman Farm of The Ohio State University in Columbus, OH (40°00'N, 83°02'W) on a Crosby silt loam soil (fine, mixed mesic Aeric Ochraqualf) (Soil Web Survey, 2009). Average temperature for 2010 was 12.0 °C, which is 0.6 °C above the historical average. Total annual precipitation was 80.54 cm, of which 46.2 cm occurred between the frost-free period of April 28th and October 22nd. The 1.4–ha site had been conventionally managed for corn and soybean rotations since 2006.

Treatments were laid out according to a randomized complete block design involving a total of 36 plots (4.33 x 6.2 m, with 2 m buffers). Each block contains factorial combinations of all treatments including a one-time biochar application (0, 5, or 25 Mg ha^{-1}) and a mineral fertilizer application (75 kg ha^{-1} or 150 kg ha^{-1}) for corn. Each block was replicated 6 times across the center of the site. Outside of the plots on both ends of the site is 0.4 ha cultivated under NT management without biochar amendment.

In April of 2010, randomly assigned plots received 14 kg or 70 kg of biochar applied by hand and incorporated by rotovator to approximately 12 cm depth. Control plots (TC) were also tilled with the rotovator to determine the effect of tillage on soil physical parameters. Soybean was planted as the first crop and, since fertilizer was not applied, there are 12 replicates of each treatment exist in the first growing season. With so many replicates, it was unnecessary to take samples from every plot in order to quantify the impact of biochar incorporation on soil physical parameters.

2.2 Biochar characterization

Biochar, obtained from a commercial charcoal producer, was pyrolyzed at 425 °C from mixed Oak (*Quercus* ssp.) wood chips in a Missouri kiln. Bulk density (ρ_b) of biochar was estimated by directly measuring dry mass and volume of 5 replicates of bulk samples. Volume was estimated using Archimedes' principle with water displacement measured in a graduated cylinder. Particle size distribution of the biochar was estimated by dry-sieving (15 minutes) in a nested stack of sieves approximately 70 g of biochar sampled from a 30 kg bag. Biochar on each sieve was weighed and the percent of total mass was calculated. This data is reported in chapter 2 of this thesis.

2.3 Soil moisture retention characteristics and saturated hydraulic conductivity

Cores were saturated for 24 hours before measuring saturated hydraulic conductivity (K_s) using the constant head method (Klute and Dirksen, 1986). After another 24 hours of saturation, cores were weighed and placed on a tension table. Suction was applied for 24 hours at each level (-1 kPa, -3 kPa, and -6 kPa) at which time the cores were moved to pressure plates for equilibration at -33 kPa, -100 kPa, and -300 kPa (Klute, 1986). Samples were weighed when equilibrium was attained (4-6 days) as indicated by the lack of discharge from the tube outlet. Soil was dried at 105 °C, and the oven dry weight was determined for each core. Soil was wet sieved through a 2 mm sieve to determine gravel and biochar contents. Approximately 20 g of the < 2 mm soil fraction from bulk samples was used to determine moisture content at –1500 kPa pressure (1.5 MPa matric potential). The θ_{AWC} was calculated as the difference between moisture content values at -33 kPa and -1500 kPa matric potentials. This value is compared to the previously mentioned field θ_{AWC} to reflect on differences between lab and field measurements.

2.4 Water infiltration

After harvest of soybean in the Fall of 2010, water infiltration rate was measured using a single-ring infiltrometer, with a 24-cm diameter (Bouwer 1986). Measurements were made once in each of 3 plots equating to 3 replicates per treatment. A 6 cm constant head was kept using the Mariotte-syphon arrangement. Average antecedent moisture conditions were determined at 0 – 10 cm, 10 – 20 cm, 20 – 30 cm soil depths to be 18 %, 20 %, and 19 %, respectively. After measurements, infiltrometers were covered with a plastic sheet for 24 hours to prevent evaporation. The plastic was removed and intact core samples of 7.5 cm diameter and length were taken from three depths (0 – 10 cm, 10 – 20 cm, and 20 – 30 cm) using a double-cylinder hammer driven core sampler (Blake and Hartge 1986).

Infiltration data were fitted to two conceptual models and one empirical model:

(1) Philip's (1957) model to compute soil water sorptivity (S) and transmissivity (A) by using numerical analysis (Eq 1 and 2):

$I = St^{1/2} + At$……………………………………………………………………..(Eq 1)

$i = ½St^{-1/2} + A$……………………………………………………………………(Eq 2) where, I is the cumulative infiltration (cm); t is elapsed time; i is instantaneous infiltration rate.

(2) The Green-Ampt model assumes a simplified physical structure which involves the use of Darcy's law to predict steady-state infiltration (K_s) (Green and Ampt 1911):

$$i = i_c + \frac{b}{I} \quad \text{(Eq 3)}$$

where i is the instantaneous infiltration rate; i_c is steady-state infiltration rate (K_s); b is a constant; and I is the cumulative infiltration (cm).

(3) The Kostiakov (1932) model provides analysis of a wide range of soils and is simple to use.

$$I = \alpha t^{\beta} \quad \text{(Eq 4)}$$

$$i = \alpha' t^{\beta'} \quad \text{(Eq 5)}$$

where I is cumulative infiltration (cm), i is instantaneous infiltration rate (cm min^{-1}), t is time (min), and α, β, α', and β' are empirically determined constants.

2.5 Soybean Yield

Above-ground biomass and grain yield of soybean were measured in each of the 36 plots at the end of the first season of biochar application. Two replicates of 1 m^2 areas were randomly selected within each plot and were harvested by clipping soybean stems at the soil surface. All harvested plants in a replicate were placed in a paper bag, dried to 14% moisture content, and weighed. After weighing the above-ground biomass, soybean plants were threshed to attain grain yield. Statistical analysis was conducted on biomass and grain yield.

2.6 Statistical Analysis

Analysis of data pertaining to soil physical properties was conducted using the PROC GLM procedure in Statistical Analysis Software 9.2 (SAS Institute, 2008). Initial sampling conducted in the fall of 2010 consisted of moisture retention, water infiltration, and saturated hydraulic conductivity. Measurements were grouped based on treatment: TB25, TB5 and TC, which are represented by 1 replicate from 3 plots for a total of 3 samples per depth. The NTC represents 3 samples per depth from the NT managed area outside of plots. Additional sampling conducted in the spring of 2011 consisted of moisture retention and saturated hydraulic conductivity. These samples were grouped based on treatment and are all from the surface (0 – 10 cm) depth. Treatments TB25 and TC are represented by 3 replicates from 6 plots for a total of 18 samples. No-till control (NTC) represents 6 samples from the no-till managed area outside of plots. All data in tables are reported as least square means of the treatment. Least significant difference (LSD) values were calculated for each depth and parameter.

The soybean above-ground biomass and grain yield were analyzed using the Proc GLM procedure based on 12 replicates of three treatments: TB25, TB5, and TC. The Tukey's Studentized Range (HSD) test provided minimum significant difference (alpha = 0.05) values to compare treatments.

Mass of biochar (> 2 mm particles) obtained from wet-sieving each core from TB25 plots and the ρ_b of biochar were used to calculate biochar concentration on a volume basis. Pearson correlation coefficients were performed to determine correlations between biochar concentration, soil physical properties, and crop yield. Significant correlations lead to linear regression equations involving biochar concentration and selected soil physical parameters.

3. Results and discussion

3.1 Moisture retention

In the 0 – 10 cm depth, moisture retention of TB25 is consistently higher than that in TB5, TC, and NTC across all moisture potentials, with the exception of – 1500 kPa (Figure 6). However, only the initial saturation was significantly (p = 0.05) more in TB25 than NTC. Comparisons among TB25, TB5, and TC suggest an increase in moisture retained at low pressure (macro-pores) probably due to tillage rather than biochar amendment. Further, there were no significant differences among treatments in low energy moisture characteristics (macropores). These data are in accord with the generalization that management practices in the short-term do not significantly impact soil micro-pore structure. Moisture retention characteristics of the 10 – 20 cm depth did not also indicate any significant differences among treatments, which is consistent with the tillage depth and that of the biochar incorporation. The significant differences observed in the 20 – 30 cm depth can only be explained by experimental error and/or high variability in soil. However, no significant differences among treatments in antecedent saturation suggests differences in soil properties rather than in experimental methodology or any experimental error.

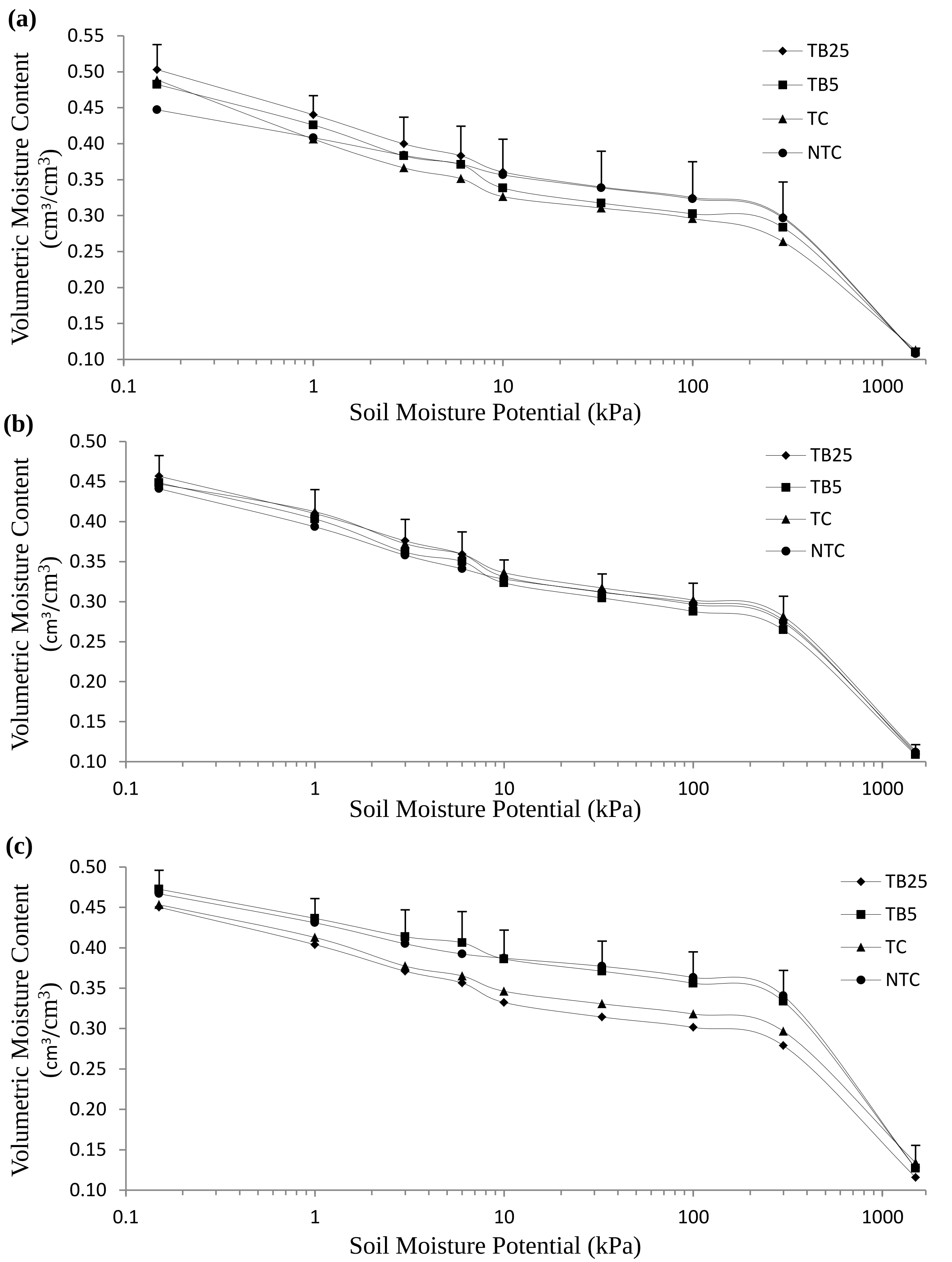

Figure 6. Soil moisture characteristic curves from 7.5 cm diameter cores of 3 depths: (a) 0 – 10 cm, (b) 10 – 20 cm, (c) 20 – 30 cm. Bars represent LSD values (p = 0.05).

Table 7. Volumetric moisture characteristics of biochar amended soil.

Depth:	0 – 10 cm			10 – 20 cm			20 – 30 cm		
Treatment	θ_{FC}	θ_{PWP}	AWC	θ_{FC}	θ_{PWP}	AWC	θ_{FC}	θ_{PWP}	AWC
TB25	0.34a	0.11a	0.23a	0.31a	0.11a	0.20a	0.31b	0.12a	0.20b
TB5	0.32a	0.11a	0.21a	0.30a	0.11a	0.20a	0.37a	0.13a	0.24a
TC	0.31a	0.11a	0.20a	0.32a	0.11a	0.20a	0.33b	0.13a	0.20b
NTC	0.34a	0.11a	0.23a	0.31a	0.11a	0.20a	0.38a	0.13a	0.25a
$LSD_{0.05}$	0.05	0.01	0.05	0.02	0.01	0.03	0.04	0.03	0.04

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = no-till managed area adjacent to plots.

There were no significant differences among treatments in the θ_{AWC} (Table 7). These data are contrary to findings in literature that suggest that biochar application increases plant AWC in soil (Laird et al. 2010; Chen et al. 2010). Secondary sampling yielded results discussed follow. Additional sampling of TB25, TC, and NTC treatments of the 0 – 10 cm depth in the spring of 2011 provided further insight into the effects of biochar incorporation. Volumetric moisture content (θ) of TB25 is consistently higher than TC and NTC across all moisture potentials, with the exception of – 1500 kPa (Figure 7). However, only initial saturation and AWC were significantly more in TB25 than the control treatments. The pF curves indicate the biochar incorporation into soil increased macro-pores related to water transmission (> 50 µm ECD). A steep decline towards – 1500 kPa indicates greater volume in pores of equivalent cylindrical diameter (ECD) between 4.5 µm and 1 µm. The larger θ values at low suction of TC from NTC reflects on the impact of tillage on soil macro-porosity.

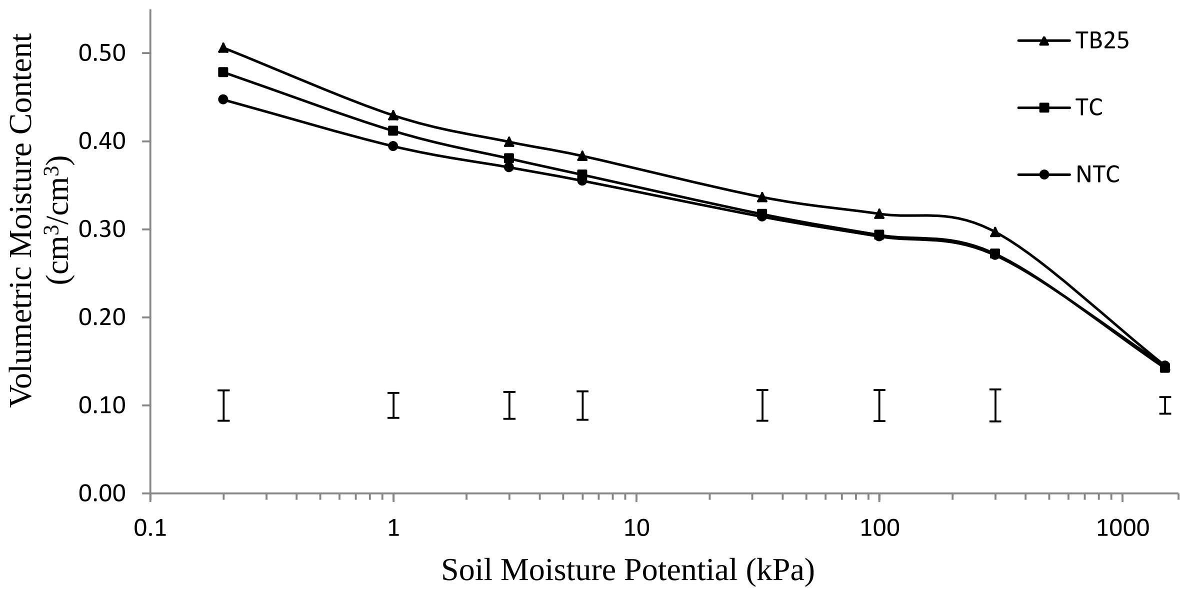

Figure 7. Soil moisture retention curves from 0 – 10 cm depth of treatments. Bars represent LSD values ($p = 0.05$) calculated for each moisture potential. TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = NT managed area adjacent to plots

3.2 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_s) data are distinctly different from spring 2011 soil samples. Biochar amendment (TB25) increased K_s by 64% and 352% over TC and NTC, respectively (Table 8). Decreasing K_s for each successive 30 minute time interval likely indicates the slow release of air bubbles trapped in pores (Table 8). Statistical analysis did not reveal any differences in changing K_s over time, but NTC decreased K_s by 31.2% while TB25 and TC decreased it by 23% and 18.8%, respectively. Significant difference has been reported for 16 Mg ha^{-1} amendment of biochar ground to 2 mm and applied to a clay loam soil in Northern Laos (Asai et al. 2009). Studies showing significant decreases in K_s with increasing biochar concentration involve sandy textured soils (Brockhoff et al. 2010). Care should be taken in interpreting K_s values, since the constant head method overestimates the true K_s value of a soil profile.

Table 8. Mean saturated hydraulic conductivity (K_s) measured over 4 x 30 minute intervals.

Treatment	Saturated Hydraulic Conductivity (cm hr^{-1})			
	K_s1	K_s2	K_s3	K_s4
TB25	121.1a	101.1a	94.2a	93.3a
TC	73.9ab	69.3ab	64.4ab	60.0ab
NTC	26.8b	22.3b	21.1b	18.4b
$LSD_{0.05}$	84.0	69.0	63.5	57.4

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = NT managed area adjacent to plots. Significant difference ($p < 0.05$) indicated by different letters attained by Tukey-Kramer adjustment for multiple comparisons.

3.3 Water infiltration

Average cumulative infiltration (cm) from 3 replicates of 4 treatments (TB25, TB5, TC, and NTC) is presented in Figure 8. Significant differences were observed between TC and NTC during the time interval between 60 minutes and 180 minutes, but not between other treatments or time intervals. Similar to K_s, high variability is also common with water infiltration measurements taken using small (< 1 m diameter) infiltrometers (Bouwer 1986). Because of high variability, as many as 20 replicate measurements are needed to obtain 10% standard deviation (Bouwer 1986). In addition, water infiltration is commonly measured to be the vertical flow of water and precautions should be taken in order to reduce lateral divergence. While the double-ring infiltrometer does not reduce lateral divergence, it does provide a better bond between the soil and inner cylinder surface, which reduces preferential flow along the inner side of the cylinder caused by disturbing the soil surface (Bouwer, 1986).

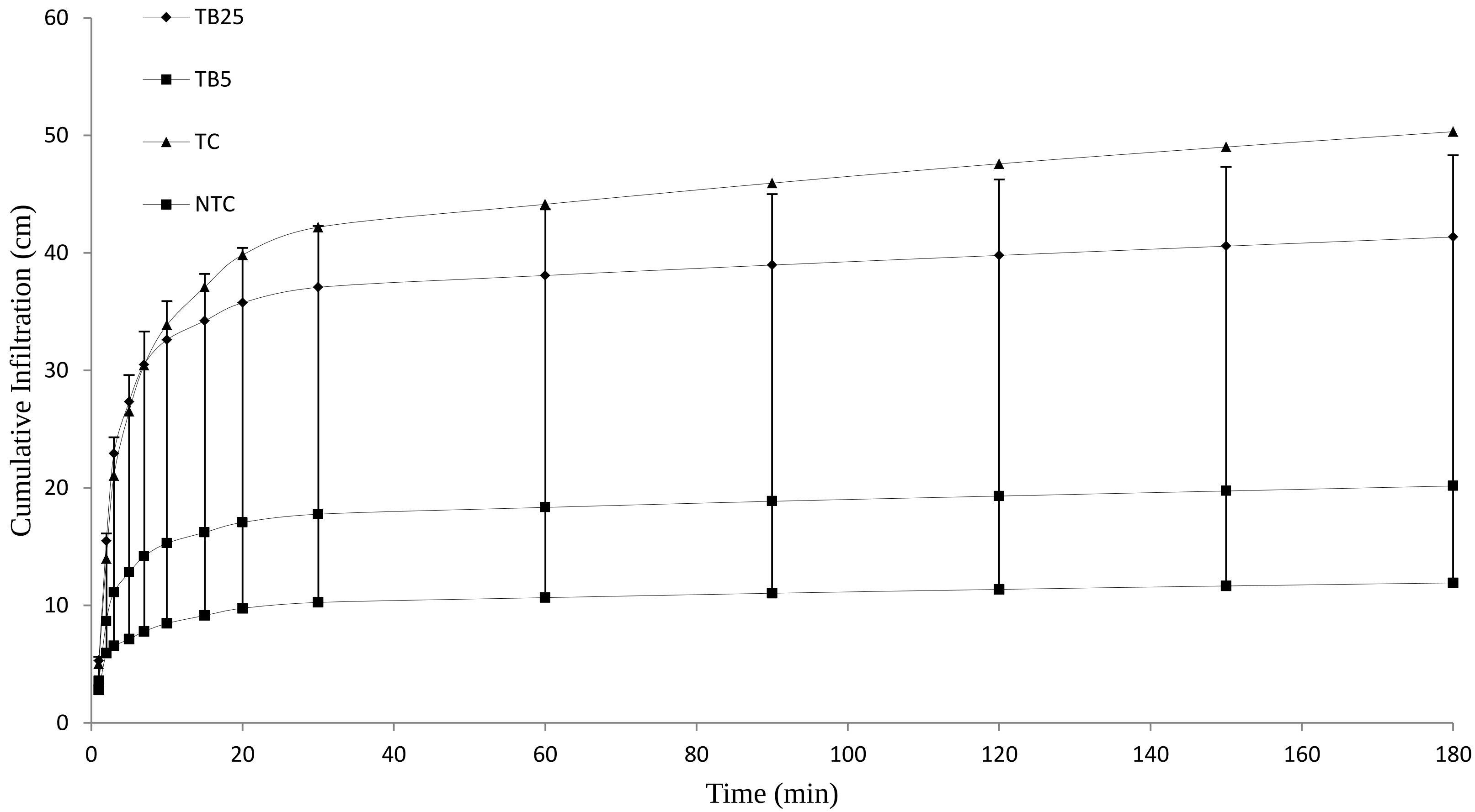

Figure 8. Cumulative infiltration (cm) as affected by biochar soil amendment and tillage. TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = No-Till managed area adjacent to plots. Bars extending upward from NTC are LSD values at each time.

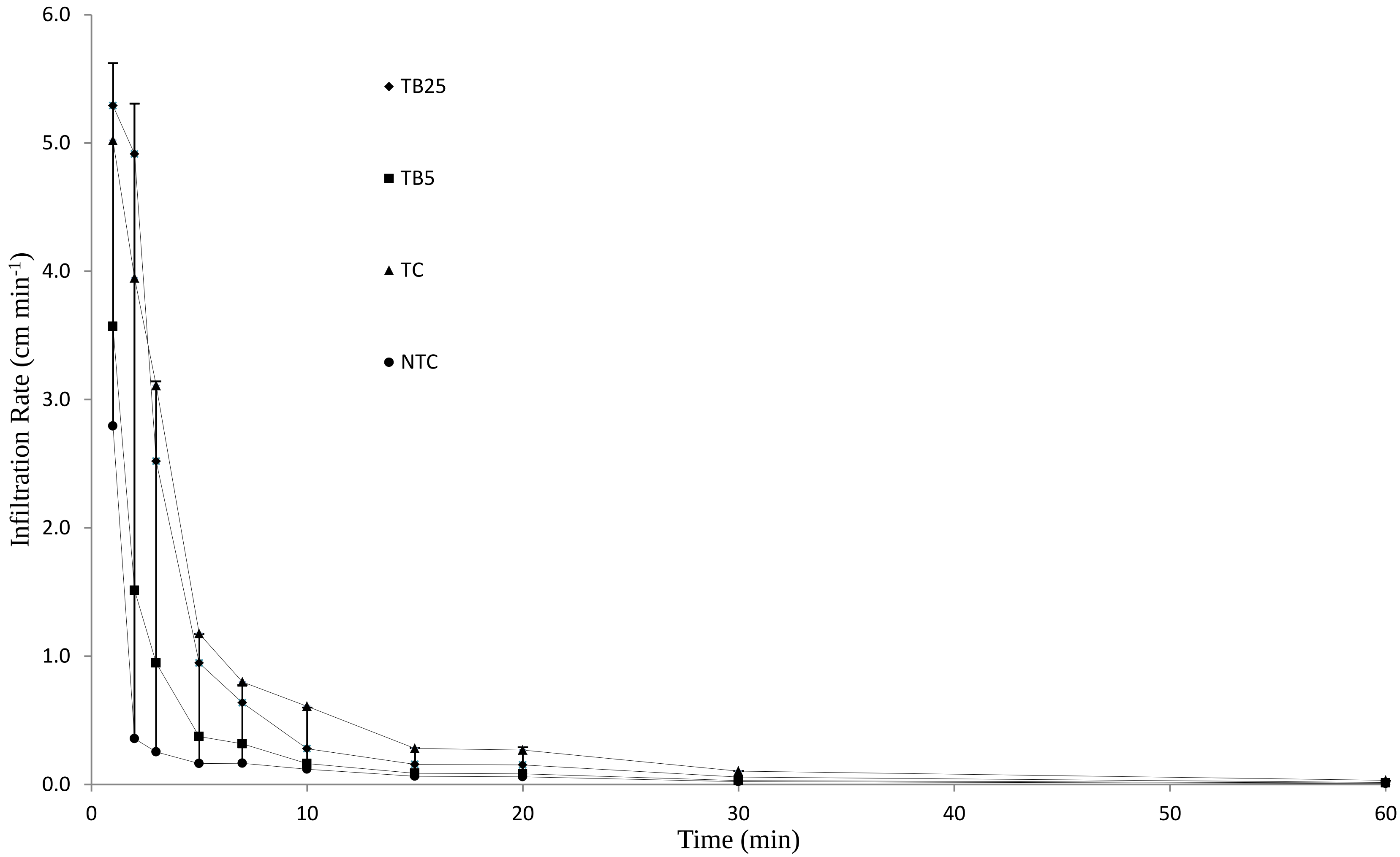

Figure 9. Infiltration rate as affected by biochar soil amendment and tillage. TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = No-Till managed area adjacent to plots. Bars extending upward from NTC are LSD values at each time.

There were no differences among treatments regarding the water infiltration rate (Figure 9). High variability and the lack of measurements resulted in high CV. Furthermore, the lack of crop residues on the surface of NTC may be the main cause of low water infiltration compared to the tilled treatments. Conversion from conventional till to NT management typically results in increased volume of 100 – 500 μm macro-pores and decreased those of 30 – 100 μm micro-pores (Kay and VandenBygaart 2002). Although previous management practices and soil type play a significant role, NT managed soils typically have significantly higher water infiltration rate due to increased macro-pores (Lin et al. 1996). Tillage improves water infiltration and aeration in agricultural soils with low macro-porosity (Carter 1988).

No significant differences were observed between parameters of Philip's and Green-Ampt's models (Table 9). Soil-water transmissivity (A) and sorptivity (S) are both impacted by management practices, especially tillage and mulching (Shukla et al. 2003; Nanbude and Mbagwu 1999). Increases in S and A are related to improved macro-pore connectivity and total porosity, respectively. Thus, TC plots exhibited enhanced A and S due to the immediate effect of tillage. Philip's model predicts negative A values for all treatments, which suggests Philip's model is not applicable to this soil (Lal and Vandoren 1990). Nonetheless, A is 39%, 97%, and 139% higher and S is 55%, 175%, and 196% higher for respective TB5, TC, and TB25 treatments than NTC. These comparisons suggest biochar may influence saturated flow (A) more than initial unsaturated flow (S).

In contrast, the Green-Ampt model suggests higher steady-state infiltration rate for NTC as compared to the tilled plots, which is supported by other studies on the effects of no-till management on water infiltration (Abid and Lal 2009), but conflicts with observed measurements of final infiltration rate (i_{180}).

Table 9. Parameters of 3 models fitted to water infiltration data.

Treatment	Instantaneous Infiltration Rate (5 and 180 min)		Philip's model		Green-Ampt model		Kostiakov model			
	i_5 (cm h^{-1})	i_{180} (cm h^{-1})	A (cm h^{-1})	S (cm $h^{-1/2}$)	b	i_c (cm h^{-1})	α	β	α'	β'
TB25	56.7a	0.75ab	-0.98a	12.6a	0.04a	2.4a	2.97a	0.24a	7.45a	-1.35a
TB5	22.4a	0.41ab	-0.57a	6.6a	0.09a	3.6a	2.33ab	0.23a	3.34a	-1.28a
TC	70.6a	1.28a	-0.81a	11.7a	0.03a	1.2a	2.92ab	0.31a	7.64a	-1.21a
NTC	9.76a	0.25b	-0.41a	4.26a	0.09a	4.2a	1.95b	0.20a	1.33a	-1.17a
$LSD_{0.05}$	60.6	1.02	1.24	18.04	0.18	0.14	0.98	0.22	14.76	0.45

Mean transmissivity (A) and sorptivity (S) of Philip (1957) equation ($i = ½St^{-1/2} + A$), Green-Ampt model ($i = i_c + b/I$) parameters b and i_c, and Kostiakov model ($I = \alpha t^{-\beta}$) alpha and beta parameters for each treatment: TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar; NTC = No-Till managed area adjacent to plots.

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Furthermore, comparisons of soil properties in chapter 2 show NTC has higher bulk density and lower total porosity which suggests slower saturated flow. Based on the lack of crop residue on the surface of the NTC area, no-till management has been poorly executed, resulting in a hard surface crust likely caused by the impact of rain drops. Hence, lower infiltration rates were observed in NTC compared to tilled plots.

The Kostiakov model resulted in significant differences between the coefficient α of TB25 and NTC (Table 9). This suggests the behavior of cumulative infiltration of TB25 is significantly different than NTC. Other parameters of the model did not exhibit significant differences, but generally trend towards higher numerical values with tillage.

3.4 Crop yield

Soybean above-ground biomass increased significantly by 8.2% and 12.3% with biochar amendment at 5 and 25 Mg ha^{-1}, respectively. On average, grain yield from TB5 and TB25 plots were 12.8% and 12.5% more than TC, respectively (Table 10). Increasing biomass with biochar concentration suggests a specific mechanism related to the concentration of biochar in the soil, such as an increase in the AWC (Laird et al. 2010). Chemical and biological analyses of soil and biochar are necessary to make appropriate convictions about the increase in soybean above-ground biomass.

Table 10. Soybean above-ground biomass and grain yield harvested from 36 plots.

Treatment	Biomass (kg ha^{-1})	Grain Yield (kg ha^{-1})
TB25	8400a	3079a*
TB5	7900ab	3086a*
TC	7300b	2736b
$LSD_{0.05}$	9600	458

TB25 = Tilled plots amended with biochar at 25 Mg ha^{-1} rate; TB5 = Tilled plots amended with biochar at 5 Mg ha^{-1} rate; TC = Tilled plots without biochar. Significant difference ($p < 0.10$) is indicated by *.

The trend in grain yield suggests that the presence of biochar, regardless of concentration, causes an increase, which might suggest the "charcoal effect" described by Graber et al. (2010). Biochemicals, either from the biochar itself, or from the microbial communities that develop after biochar is applied, stimulate plant growth. Chemical and biological analyses of soil and biochar are necessary to make appropriate convictions about the increase in soybean grain yield.

3.5 Correlations and linear regression

Correlations between pore size and properties include (i) pores of 0.1 μm ECDs declined with increasing biochar concentration (g g^{-1}), and (ii) pores of 1500 μm and 0.5 μm ECDs increased with increasing biochar concentration. Predicted trends in ρ_b, f_t, K_s, and AWC of soil with biochar concentration are supported by the data in Table 5. Typical trends in biochar amended soil including ρ_b, f_t, K_s, and θ_{FC} are supported by correlations with pores of 1500 μm and 0.1 μm ECDs (Table 11). The strongest correlation is between biochar concentration and AWC, which results from the high concentration of pores with 0.5 μm ECD. Biochar reduces the concentration of pores of 0.1 μm ECD, which reduces the amount of moisture held by pores too small to be accessed by plant roots.

Biomass and grain yield both have positive correlations with f_t and negative correlations with ρ_b, indicating that soil properties improved for soybean growth with the application of biochar. The positive correlations with pore size 1500 μm ECD and biomass indicate that soil amended with biochar has better aeration and water transmission properties than unamended soil. Enhanced biomass and grain yield may have resulted from biochar amendment impacting pore sizes related to moisture retention (AWC) and water infiltration rate (i_c). However, chemical and biological analyses of soil and biochar are necessary to make appropriate convictions about the increase in biomass.

Table 11. Pearson's correlation coefficients for biochar concentration and measured parameters. All soil parameters and biochar concentration data comes from 21 core samples from TB25 plots.

	Biochar	ρb	f_t	K_s	θ_{FC}	AWC	ECD_{1500}	$ECD_{0.5}$	$ECD_{0.1}$	Biomass	Grain
Biochar	1.00	–	–	–	–	–	–	–	–	–	–
ρb	–0.51*	1.00	–	–	–	–	–	–	–	–	–
f_t	0.51*	–0.99*	1.00	–	–	–	–	–	–	–	–
K_s	0.48*	–0.41**	0.39**	1.00	–	–	–	–	–	–	–
θ_{FC}	0.33^{ns}	–0.46*	$–0.05^{ns}$	–0.42*	1.00	–	–	–	–	–	–
AWC	0.75*	$–0.06^{ns}$	0.09^{ns}	0.16^{ns}	0.49*	1.00	–	–	–	–	–
ECD_{1500}	0.42**	–0.72*	0.72*	0.57*	$–0.24^{ns}$	$–0.05^{ns}$	1.00	–	–	–	–
$ECD_{0.5}$	0.61*	0.04^{ns}	$–0.02^{ns}$	$–0.01^{ns}$	0.47*	0.94*	$–0.22^{ns}$	1.00	–	–	–
$ECD_{0.1}$	–0.38**	0.84*	–0.85*	–0.41**	0.28^{ns}	$–0.10^{ns}$	–0.63*	$–0.01^{ns}$	1.00	–	–
Biomass	0.60*	–0.67*	0.66*	0.63*	$–0.03^{ns}$	0.20^{ns}	0.59*	0.18^{ns}	–0.60*	1.00	–
Grain	0.51**	–0.69*	0.66*	0.48**	$–0.09^{ns}$	$–0.07^{ns}$	0.63*	$–0.05^{ns}$	–0.50*	0.86*	1.00

Statistical significance at the $p < 0.10$ level is indicated by *; statistical significance at the $p < 0.10$ level is indicated by **; while no statistical significance is indicated by ^{ns}.

Using linear regression analysis in SAS 9.2 software, linear equations were estimated to predict soil property responses based on biochar concentration (Table 12).

Table 12. Linear regression equations of select soil parameters. Fitted β_0 and β_1 parameters for the linear equation, y = β_0(x) + β_1, where y is a soil property or plant response and x is the biochar concentration (g g^{-1}).

Property	β_0	β_1	p statistic	r^2
ρb	– 3.89	1.41	0.015	0.26
f_t	1.45	0.47	0.015	0.26
K_s	2743.2	25.0	0.025	0.23
θ_{FC}	1.02	0.43	0.128	0.11
AWC	1.4	0.17	0.0001	0.56
ECD_{15000}	240.5	19.4	0.051	0.18
$ECD_{4.5}$	390.9	43.3	0.003	0.37
ECD_1	-124.1	50.6	0.079	0.15
Biomass	40954	7332.4	0.024	0.36
Grain	17491	2737.1	0.063	0.26

Using AWC and soybean above-ground biomass as examples from Table 12, data can be graphed and used to predict a response based on the concentration of biochar in soil (Figure 10).

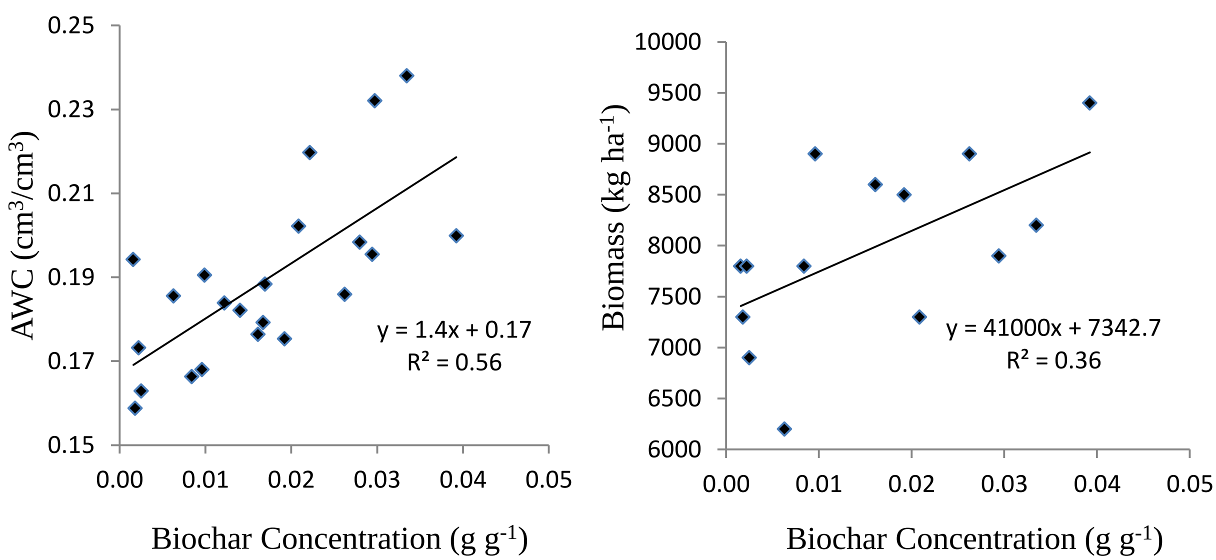

Figure 10. AWC and soybean above-ground biomass relationships with biochar concentration in soil.

The correlation between AWC and biochar concentration is moderate (r^2 = 0.56), yet variable, evident by the approximately 0.04 cm^3 cm^{-3} AWC spread at both 0.02 and 0.03 g of biochar g^{-1} of soil concentrations. Linear regression of other parameters, including biomass, yields weaker correlations with biochar concentration, yet still provide insight into the mechanisms that biochar influence with regards to soil hydrological and mechanical properties. Furthermore, care should be taken in interpreting correlations, as correlation does not mean causation. Chemical and biological analyses of biochar and soil should be conducted in order to

4. Discussion

The data presented indicate that some potential effects of biochar incorporation on soil physical characteristics may have been masked by the effects of tillage. This seems plausible since the pore size distribution of biochar is theoretically much different than that of a heavy-textured soil (Downie 2009). Nonetheless, data from field samples and lab moisture extraction suggest that biochar application enhances moisture retention in this agricultural soil, even only 6 months after tillage. Also, biochar incorporation resulted in significant increases in saturated hydraulic conductivity of the 0 – 10 cm depth, and also may have enhanced water infiltration. However, water infiltration did not indicate significant differences with regards to biochar amendment, while tillage did impact water infiltration. Longer term analysis of hydrological changes regarding biochar in soil is necessary to understand how the pore structure changes over time. For example, tillage likely impacted the stability of macro-aggregates, which leads to increased slaking when soil is rapidly wetted. An increase in micro-aggregates and available primary particles eventually causes soil pores below the tilled zone to clog, thereby increasing bulk density. This process suggests that any improvement in porosity attributed to biochar amendment may have been masked by the adverse effect of tillage. Since the tillage in this experiment is a single event specifically used to rapidly incorporate biochar into the soil, then there may have been a significant clogging of biochar pores leading to impeded hydrological performance. Analysis of soil characteristics after the soil structure develops under NT management may provide insight into biochar's influence on soil processes.

Additionally, correlations between biochar concentration, soil properties, and soybean yield were significant in the first year of biochar amendment. Linear regression analysis provides an opportunity to predict future changes in soil properties with regards to the biochar used in this study (hardwood chips). Continued monitoring of crop yield, and analysis of both soil nutrients and microbial activity would provide a more complete picture of soil processes impacted by biochar amendment.

5. Conclusion

Biochar incorporation into soil has an immediate impact on moisture retention and hydraulic conductivity. Water infiltration measurements yielded conflicting results that were likely a result of high variability related to tillage. Furthermore, larger double-ring infiltrometers combined with more replicates may provide better representation of treatments. Correlation and linear regression analysis indicated soil AWC and hydraulic conductivity increases with biochar concentration, mainly because of the change in pore size distribution. Additionally, correlations indicate soil properties may be influenced, but not entirely, by biochar concentration.

Correlations between tillage and soil properties should be conducted. Upon further analysis of correlation coefficients and linear regression, it was decided that much more evidence, including chemical and biological analysis of soil and biochar, is necessary to have conviction about the enhanced soybean biomass and grain yield.

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Chapter 4: Summary and Conclusion

General Discussion

Mechanical and hydrological soil properties

The data presented in this thesis suggests biochar directly influences the mechanical properties of soil which, in turn, influences the hydrological properties of soil. Physical characterization of biochar is important for understanding impacts on soil physical processes. Both the particle size distribution and tensile strength (TS) of biochar provide insight into stability in soil. In temperate climates, soils experience regular freeze/thaw cycles (FTCs), which have been shown to influence labile soil organic matter (SOM) while having no impact on recalcitrant SOM (Feng et al. 2007). Data from chapter 2 shows a shift in particle size distribution of wood-chip biochar to smaller particles likely due FTCs influence on biochar TS. While biochar breaks into smaller particles from FTCs, the lack of significant changes in fractions < 0.25 mm suggest it is unlikely that significant amounts of biochar percolate through the soil in the form of dissolved organic carbon (DOC) or particulate organic carbon (POC), since intense rainfall did not mobilize more than 1% of biochar in tropical soils (Major et al. 2010). This is important in determining biochar rate and number of applications to soil, since farmers typically apply liming agents and fertilizers on regular intervals. Furthermore, the transition of particles from > 2 mm to < 2 mm caused by FTCs suggests soil total porosity (f_t) may continue to improve with each subsequent season.

Recalcitrance of biochar indicates application to temperate agricultural soils has a low risk of depreciating value, and provides significant environmental and agronomic benefits.

Biochar has been identified as an effective soil conditioner (Kishimoto and Sugiura 1985), evident in chapter 2 as a decrease in soil bulk density (ρ_b) and the attendant increase in f_t (Laird et al. 2010; Oguntunde et al. 2008; Jones et al. 2010). In agriculture, soil compaction restricts root development and, therefore, crop yield. Various forms of plowing are typically implemented to manage soil compaction, but provides temporary relief and has adverse impacts on soil aggregation, a process that has been described as being just as important to the continuance of life as photosynthesis (Jacks 1963). Other management practices including, mulching and crop rotations, enhance soil aggregation which alleviates compaction using biological processes to increase pore space. The combination of reduced ρ_b from 1.57 Mg ha^{-1} to 1.28 Mg ha^{-1} and high tensile strength of biochar partices (chapter 2) suggests that incorporation of biochar into soil provides a long-term alleviation of soil compaction.

While aggregation is a primary indicator of soil structure in terms of physical barriers, assessment of soil pore size distribution provides an alternative perspective with regards to fluid movement. The increase in f_t associated with biochar amendment to soil suggests changes in pore size distribution that favor specific moisture processes and subsequent biological and chemical processes within soil. Evidence in chapter 2 suggests biochar enhances macro-pores of equivalent cylindrical diameter (ECD) 1500 µm and mesopores of ECD 25 µm and 0.5 µm. Macro-pores are essential in water transmission through soil, while meso-pores store water for plant growth and biological processes. More specifically, plant available water capacity (AWC) is a measurement of all pore sizes that can retain water accessible by plant roots. Evidence from chapter 2 shows biochar (25 Mg ha^{-1}) increases AWC by 11% and 41% over till and no-till controls, respectively. Other studies have reported much greater increases in AWC: 63% and 147% with respective 40 and 80 Mg ha^{-1} biochar amended sand and 214% and 370% with respective 20% and 25% by volume biochar amended sand (Jones et al. 2010; Brockhoff et al. 2010). Improvements in AWC depend on biochar type and soil type (Busscher et al. 2010; Tryon 1948). Furthermore, chapter 3 displays evidence of biochar amendment at 25 Mg ha^{-1} enhancing moisture retention over control treatments (TC and NTC), which has implications for protecting plant growth of crops experiencing water stress (Laird et al. 2010). Increasing plant resilience to water stress becomes increasingly important as climate change exaggerates such conditions, even in soils that don't usually experience water stress.

The increase in macro-pores as a result of biochar amendment suggests enhances water transmission, which is important during heavy precipitation leading to ponding and surface run-off. Measurements of saturated hydraulic conductivity (K_s) using the constant-head method in the lab provided insight into the effect of biochar amendment on soil water transmission. Clayey soils responds to biochar amendment (TB25) with increased K_s by 56% and 407% over TC and NTC. In contrast, K_s of sand decreases with increasing biochar amendment (Brockhoff et al. 2010). Furthermore, a study on charcoal production sites (CCS) provides, to date, the best insight into long-term changes in hydro-physical changes in a sandy textured soil in Ghana (Oguntunde 2008). An 88% increase in K_s over adjacent field sites (AFS) was corroborated with a 9% decrease in ρ_b and a 10.7% increase in f_t.

Correlations between biochar amendment rates and crop productivity suggest multiple mechanisms depending on soil type, biochar type, and climate. Data in chapter 3 shows TB5 and

TB25 with increases in soybean above-ground biomass of 8.2% and 12.3%, respectively over TC. Grain yield of TB5 and TB25 resulted in respective 12.8% and 12.5% increases over TC. Soybean biomass likely responds to AWC which increases with biochar concentration (Blackwell et al. 2010), while grain yield might respond to some form of chemical stimulus (The charcoal effect) from biochar amendment (Graber et al. 2010). Favorable moisture retention and flow characteristics combined with increasing pH and nutrient availability in CCS resulted in 91% and 276% increases in maize grain yield over AFS (Oguntunde et al. 2004; 2008). Biochar as a weak liming agent increases soil pH causing increased nutrient availability and decreased aluminum toxicity in normally acidic tropical soils (Major et al. 2010). Agricultural soils with such conditions result in the greatest improvements in crop yield.

Until now, linear regression equations have not been developed between biochar concentrations in soil and soil physical properties. Biochar concentration was estimated by physical recovery of particles > 2 mm diameter which consisted 95% of total biochar applied to soil. The average biochar concentration of 22 samples analyzed was 0.017 g g^{-1} (0.034 cm^3 cm^{-3}) with a minimum of 0.002 g g^{-1} (0.004 cm^3 cm^{-3}) and a maximum of 0.039 g g^{-1} (0.077 cm^3 cm^{-3}). Significant correlations were observed among several soil properties and soybean yield, but strong correlations are noted below:

$y = 1.4(x) + 0.17$ (where "y" is AWC and "x" is biochar concentration).

$y = 390.9(x) + 43.3$ (where "y" is ECD 0.5 μm and "x" is biochar concentration).

$y = 40954(x) + 7332.4$ (where "y" is soybean above-ground biomass and "x" is biochar concentration).

These linear regression equations can be used to predict soil and plant responses to biochar amendment.

Conclusion

Incorporation of biochar into modern agriculture provides opportunities to address significant agronomic issues. Production of biochar through pyrolysis provides biofuels that can offset fossil fuel use while fixing a significant portion of the carbon (C) to the recalcitrant fraction of the terrestrial C pool, thereby enhancing C sequestration from the atmospheric C pool to mitigate global climate change. Subsequent application of biochar to agricultural soils enhances porosity providing space for additional moisture and nutrients, microbial habitat, and water infiltration which in turn have a positive impact on plant production, soil quality, and reduced run-off associated with non-point source pollution. Furthermore, biochar has potential to mitigate environmental problems related to agricultural nutrient loss through greenhouse gas emissions and eutrophication of water bodies. As research gains depth into the effects of biochar incorporation into soil, it is becoming more apparent that modern agriculture would benefit from establishing biochar as a best management practice (BMP). With this in mind, careful thought must be taken in constructing, maintaining, regulating, and implementing industrial-scale biochar production facilities.

In a general sense, rapid adoption of biochar as a BMP may induce unintended consequences that can lead to profligate use of natural resources. Severe risks associated with barren soils from biomass removal for the production of biochar include accelerated erosion, soil compaction, and nutrient losses which would offset any benefits from biochar incorporation into soils. Removal of biomass that would otherwise contribute to net primary productivity or decompose to provide energy for soil biota can lead to the degradation of soil habitats. Feedstock selection includes compromising between harvesting a highly valued species for producing a quality biochar and sustaining or regenerating the environment in which the feedstock inhabits. Careful planning should be implemented in order to identify considerate practices for biomass removal of quality feedstock. It seems that many of these issues are being considered by those who are developing a biochar standard (see International Biochar Initiative website).

Research opportunities

Current scientific understanding of biochar and soil processes is fairly rudimentary. Much more research is necessary to determine the mechanisms upon which biochar amendment impacts processes within the soil environment (Sohi et al. 2009). For example, the role of recalcitrant C in soil aggregation processes has yet to be assessed. Most research has been focused on highly degraded tropical soils with short-term observations. Long-term field studies will provide more accurate predictive abilities as well as potential unforeseen complications. This is especially important in determining life-cycle analysis of implementing biochar production at commercial scale. In addition, much research potential exists in characterizing biochar based on feedstock and pyrolysis conditions.

Long-term studies to determine the mechanisms upon which crop yield responds to biochar soil amendment are necessary before the technology is widely adopted. Chemical and biological studies on "the charcoal effect" will provide insight into mechanisms related to plant growth stimulation and soil microbial diversity. Determining related chemical and biological compounds will also provide predictive potential for certain types of biochar in terms of enhanced plant productivity. In addition, studies to determine changes in soil microbial diversity with the presence of biochar may have significant findings in genetics.

The amount of highly degraded or unproductive land provides opportunity, in some cases, to re-establish a diverse soil and plant environment for the purposes of biofuel/crop production or C sequestration through afforestation. Such soil conditions are typically not conducive for re-establishment, but biochar amendment combined with cover cropping and efficient fertigation could provide the necessary remediation for proper establishment. Regardless, much research potential exists in examining interaction effects between biochar and other forms of soil remediation techniques. Furthermore, the environmental applications of biochar are plenty and offer significant opportunities to find ways to use this ancient technology.

Reflection

Thinking back on the experimental design and follow through of soil sampling, I would have changed two major aspects. First, the design should have included a surface applied biochar amendment to no-till plots. The excess in plot replication provided this opportunity. Second, sampling and field measurements should have been conducted in reverse order. I should have sampled only the surface depth (0 – 10 cm) with the least number of plots and the least number of samples in order to adequately correlate soil physical characteristics to soybean yield in the fall of 2010. Subsequently, I should have conducted a comprehensive soil physical characteristic evaluation (including double-ring infiltration of every plot) in the spring of 2011 before corn sowing so as to assess changes after 1 year of biochar amendment.

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Appendix A: Fall 2010 Data

Treatment	Depth	w	pb	θfc	ft	fa
TC	0	0.24	1.23	0.30	0.53	0.24
TC	0	0.25	1.29	0.32	0.51	0.18
TC	0	0.24	1.46	0.35	0.44	0.09
TB5	0	0.22	1.47	0.33	0.44	0.11
TB5	0	0.24	1.35	0.32	0.49	0.16
TB5	0	0.25	1.38	0.34	0.47	0.13
TB25	0	0.30	1.36	0.41	0.48	0.07
TB25	0	0.28	1.28	0.36	0.51	0.15
TB25	0	0.30	1.20	0.37	0.54	0.18
NTC	0	0.22	1.58	0.34	0.40	0.05
NTC	0	0.22	1.60	0.35	0.39	0.05
NTC	0	0.23	1.53	0.36	0.41	0.05
TC	10	0.21	1.46	0.31	0.45	0.14
TC	10	0.20	1.59	0.32	0.40	0.08
TC	10	0.18	1.64	0.30	0.38	0.08
TB5	10	0.20	1.54	0.31	0.41	0.10
TB5	10	0.19	1.50	0.29	0.43	0.14
TB5	10	0.19	1.56	0.29	0.41	0.12
TB25	10	0.23	1.47	0.33	0.44	0.11
TB25	10	0.21	1.56	0.33	0.41	0.08
TB25	10	0.21	1.48	0.31	0.43	0.12
NTC	10	0.23	1.49	0.34	0.44	0.09
NTC	10	0.18	1.56	0.28	0.40	0.12
NTC	10	0.21	1.51	0.32	0.42	0.10
TC	20	0.20	1.55	0.31	0.41	0.10
TC	20	0.21	1.56	0.32	0.41	0.09
TC	20	0.18	1.53	0.28	0.42	0.13
TB5	20	0.19	1.65	0.31	0.38	0.06
TB5	20	0.22	1.58	0.35	0.40	0.05
TB5	20	0.20	1.57	0.32	0.40	0.08
TB25	20	0.20	1.54	0.32	0.42	0.10
TB25	20	0.20	1.45	0.29	0.45	0.16
TB25	20	0.20	1.54	0.30	0.41	0.11
NTC	20	0.19	1.63	0.31	0.38	0.08
NTC	20	0.20	1.52	0.31	0.42	0.11
NTC	20	0.25	1.50	0.38	0.42	0.04

Treatment	Depth	VMC0	VMC1	VMC3	VMC6	VMC10	VMC33	VMC100	VMC300	VMC1500
TC	0	0.46	0.40	0.38	0.37	0.36	0.35	0.33	0.28	0.12
TC	0	0.50	0.41	0.36	0.34	0.31	0.29	0.27	0.25	0.11
TC	0	0.51	0.41	0.36	0.35	0.31	0.30	0.28	0.26	0.11
TB5	0	0.47	0.42	0.36	0.34	0.33	0.32	0.30	0.28	0.10
TB5	0	0.48	0.41	0.38	0.37	0.33	0.30	0.29	0.27	0.11
TB5	0	0.49	0.45	0.41	0.40	0.36	0.33	0.32	0.30	0.11
TB25	0	0.50	0.43	0.38	0.36	0.34	0.32	0.30	0.27	0.11
TB25	0	0.50	0.44	0.39	0.37	0.34	0.32	0.30	0.28	0.11
TB25	0	0.51	0.46	0.43	0.42	0.40	0.38	0.37	0.35	0.11
NTC	0	0.43	0.40	0.37	0.36	0.35	0.33	0.31	0.29	0.11
NTC	0	0.47	0.42	0.39	0.38	0.35	0.33	0.32	0.30	0.11
NTC	0	0.44	0.40	0.39	0.38	0.37	0.35	0.33	0.29	0.10
TC	10	0.44	0.42	0.37	0.36	0.35	0.33	0.31	0.29	0.12
TC	10	0.44	0.41	0.37	0.36	0.33	0.31	0.30	0.28	0.11
TC	10	0.46	0.41	0.37	0.36	0.33	0.31	0.29	0.27	0.12
TB5	10	0.45	0.41	0.35	0.34	0.33	0.31	0.29	0.25	0.10
TB5	10	0.44	0.39	0.36	0.35	0.32	0.30	0.28	0.27	0.11
TB5	10	0.46	0.41	0.37	0.36	0.33	0.31	0.29	0.28	0.11
TB25	10	0.44	0.40	0.36	0.34	0.32	0.30	0.28	0.26	0.11
TB25	10	0.45	0.42	0.38	0.36	0.33	0.32	0.31	0.29	0.10
TB25	10	0.48	0.42	0.39	0.38	0.34	0.32	0.31	0.29	0.11
NTC	10	0.43	0.37	0.33	0.32	0.31	0.30	0.28	0.25	0.12
NTC	10	0.45	0.41	0.38	0.35	0.33	0.31	0.30	0.28	0.11
NTC	10	0.45	0.40	0.37	0.35	0.34	0.33	0.32	0.29	0.10
TC	20	0.45	0.42	0.37	0.35	0.34	0.32	0.31	0.29	0.13
TC	20	0.46	0.41	0.37	0.35	0.33	0.32	0.30	0.28	0.11
TC	20	0.45	0.41	0.39	0.39	0.37	0.35	0.34	0.32	0.16
TB5	20	0.46	0.43	0.40	0.39	0.39	0.38	0.36	0.33	0.11
TB5	20	0.47	0.44	0.42	0.41	0.38	0.37	0.35	0.33	0.13
TB5	20	0.48	0.44	0.42	0.41	0.39	0.37	0.36	0.33	0.14
TB25	20	0.44	0.40	0.37	0.35	0.33	0.31	0.29	0.27	0.11
TB25	20	0.46	0.40	0.36	0.34	0.32	0.30	0.30	0.28	0.11
TB25	20	0.46	0.42	0.39	0.38	0.35	0.33	0.31	0.29	0.12
NTC	20	0.44	0.40	0.37	0.36	0.35	0.34	0.32	0.30	0.13
NTC	20	0.48	0.44	0.41	0.40	0.40	0.39	0.38	0.36	0.11
NTC	20	0.48	0.45	0.43	0.41	0.41	0.40	0.38	0.36	0.14

Treatment	Depth	PSD15000	PSD1500	PSD500	PSD250	PSD45	PSD15	PSD5	PSD1
TC	0	10.27	7.83	7.67	3.99	2.67	3.63	4.49	16.28
TC	0	11.48	18.34	17.96	6.84	8.95	6.73	5.06	7.7
TC	0	18.34	15.48	14.2	4.03	13.24	5.42	4.96	8.06
TB5	0	7.64	9.78	20.56	5.03	4.33	5.03	5.21	6.71
TB5	0	13.6	10.32	9.47	2.99	13.96	7.64	5.07	6.79
TB5	0	7.95	6.82	12.44	4.1	14.2	8.1	4.57	5.39
TB25	0	12.32	11.82	15.95	6.13	8.07	7.31	4.53	11.71
TB25	0	8.67	11.9	14.42	6.62	9.49	7.81	4.96	8.87
TB25	0	9.91	7.78	9.84	3.7	4.9	5.55	5.1	6.25
NTC	0	3.89	7.34	10.36	3.28	4.03	5.74	5.33	6.97
NTC	0	8.95	7.61	8.92	5.42	7.78	6.29	3.67	6.82
NTC	0	5	5.76	5.03	3.55	3.03	5.86	6.3	12.84
TC	10	0.97	3.92	17.7	3.69	4.05	6.18	6.08	5.73
TC	10	2.86	9.2	10.75	5.68	7.65	6.5	4.03	6.5
TC	10	6.56	10.95	11.26	3.55	11.37	6.28	4.9	8.12
TB5	10	3.15	7.91	19.26	4.79	4.56	5.82	7.53	11.05
TB5	10	5.3	10.61	10.41	3.17	10.72	6.38	4.19	5.73
TB5	10	8.99	8.95	11.51	3.73	11.23	6.58	4.93	6.2
TB25	10	6.7	7.9	11.95	6.36	7.31	7.11	5.1	8.53
TB25	10	3.4	9.23	12.39	6.51	8.15	5.51	3.68	6.78
TB25	10	10.34	8.79	9.53	3.67	12.49	6.78	3.75	6.71
NTC	10	8.75	11.55	10.95	4.75	2.6	4.72	6.08	8.7
NTC	10	3.66	7.96	12.62	7.07	7.8	7.19	4.41	6.24
NTC	10	4.48	10.89	11.62	5.02	2.34	4.19	5.02	7.2
TC	20	2.58	10.13	16.29	4.53	4.49	5.59	5.14	7.47
TC	20	5.72	10.74	12.59	5.72	7.33	5.24	3.68	6.94
TC	20	4.01	7.13	6.32	1.82	7.06	4.65	3.69	6.85
TB5	20	3.98	7.15	8.35	2.78	2.08	3.84	5.83	8.69
TB5	20	2.95	8.65	7.16	2.35	8.66	5.61	4.27	6.33
TB5	20	3.57	9.59	7.12	2.27	9.09	5.78	4.61	7.37
TB25	20	4.73	8.35	10.37	5.59	7.09	6.39	4.81	8.36
TB25	20	8.84	10.37	12.81	5.76	7.1	5.16	3.18	6.12
TB25	20	4.85	8.86	9.45	3.16	9.82	6.4	4.69	8.03
NTC	20	3.86	9.39	10.16	4.74	2.07	4.17	5.44	7.31
NTC	20	1.8	9.65	8.97	3.71	1.44	2.7	3.26	7.69
NTC	20	1.8	9.21	6.65	4.07	1.71	3.14	5.02	7.57

Treatment	2	4.5	7	12	17
TB25	135	275	460	1000	
TB25	100	260	385	1000	
TB25	50	100	155	1000	
TB25	150	265	300	610	1000
TB25	120	190	390	1000	
TB25	105	265	695	1000	
TB25	120	240	525	1000	
TB25	105	205	220	470	1000
TB25	105	140	160	310	1000
TB25	50	130	200	800	1000
TB25	100	240	440	1000	
TB25	40	180	340	1000	
TB25	160	220	400	1000	
TB25	80	160	220	1000	
TB25	125	190	620	590	1000
TB5	100	110	200	490	1000
TB5	50	100	150	230	1000
TB5	160	220	610	1000	
TB5	360	940			
TB5	110	250	680	1000	
TB5	240	440	690	1000	
TB5	200	260	360	1000	
TB5	180	220	250	600	1000
TB5	165	205	295	1000	
TB5	100	140	150	600	1000
TB5	120	340	890		
TB5	120	300	570	900	
TB5	100	260	620	1000	
TB5	120	190	260	680	1000
TB5	160	260	500	1000	
TC	100	180	440	1000	
TC	80	130	265	635	900
TC	110	120	180	310	1000
TC	260	310	550	1000	
TC	120	140	220	700	1000
TC	140	320	520	1000	
TC	120	260	460	1000	

TC	50	120	140	400	1000
TC	80	160	240	600	1000
TC	120	155	160	200	280
TC	50	160	500	820	1000
TC	160	200	250	850	1000
TC	260	400	700	890	1000
TC	140	340	420	1000	
TC	120	200	300	460	1000
NTC	205	510	860		
NTC	150	510	1000		
NTC	170	280	700	1000	
NTC	420	900			
NTC	230	640	1000		
NTC	340	900			
NTC	120	600	1000		
NTC	140	700	1000		
NTC	160	600	900		
NTC	240	1000			
NTC	220	610	1000		
NTC	660	1000			
NTC	260	680	1000		
NTC	540	1000			
NTC	370	620	1000		

Treatment	Plot		1	2	3	5	7	10	15	20	30	60	90	120	150	180
TB25	33	i	5.42	3.28	2.02	1.01	0.66	0.53	0.23	0.26	0.09	0.03	0.03	0.02	0.02	0.02
TB25	33	I	5.42	14.11	19.40	23.43	26.77	29.69	32.45	34.92	37.08	38.70	40.22	41.63	43.00	44.41
TB25	28	i	2.65	1.39	0.38	0.09	0.14	0.01	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
TB25	28	I	2.65	6.68	8.44	9.01	9.49	9.80	9.95	10.10	10.25	10.46	10.63	10.79	10.92	11.04
TB25	21	i	7.81	10.08	5.17	1.73	1.10	0.29	0.21	0.19	0.07	0.02	0.02	0.01	0.01	0.01
TB25	21	I	7.81	25.70	40.95	49.58	55.25	58.33	60.27	62.26	63.89	65.09	66.06	66.95	67.81	68.63
TB5	34	i	2.02	1.13	0.76	0.31	0.25	0.18	0.09	0.10	0.03	0.01	0.01	0.01	0.01	0.01
TB5	34	I	2.02	5.17	7.06	8.44	9.58	10.62	11.62	12.55	13.32	13.96	14.59	15.12	15.70	16.34
TB5	27	i	4.79	2.77	1.64	0.63	0.50	0.21	0.14	0.10	0.04	0.01	0.01	0.01	0.01	0.01
TB5	27	I	4.79	12.35	16.76	19.65	21.92	23.56	24.87	26.03	26.92	27.70	28.37	28.94	29.44	29.86
TB5	20	i	3.91	0.63	0.44	0.17	0.19	0.10	0.04	0.06	0.02	0.00	0.00	0.00	0.00	0.00
TB5	20	I	3.91	8.44	9.51	10.30	11.02	11.69	12.16	12.61	13.05	13.36	13.63	13.86	14.08	14.30
TC	32	i	5.10	5.17	3.65	1.29	0.63	0.43	0.18	0.16	0.04	0.02	0.02	0.02	0.02	0.01
TC	32	I	5.10	15.37	24.19	30.43	34.27	36.81	39.02	40.75	41.98	43.00	44.11	45.15	46.12	46.98
TC	29	i	4.41	1.26	1.13	0.47	0.50	0.29	0.15	0.14	0.07	0.02	0.02	0.01	0.01	0.01
TC	29	I	4.41	10.08	12.47	14.55	16.50	18.39	20.03	21.49	22.93	24.26	25.37	26.29	27.13	27.95
TC	22	i	5.54	5.42	4.54	1.76	1.26	1.10	0.50	0.50	0.19	0.05	0.05	0.05	0.04	0.04
TC	22	I	5.54	16.50	26.46	34.52	40.57	46.40	52.24	57.25	61.66	65.16	68.35	71.32	73.79	76.03
NTC	38	i	2.77	0.44	0.13	0.20	0.12	0.06	0.06	0.05	0.02	0.01	0.01	0.01	0.00	0.00
NTC	38	I	2.77	5.98	6.55	7.09	7.73	8.15	8.64	9.20	9.71	10.17	10.58	10.94	11.26	11.54
NTC	40	i	2.90	0.38	0.25	0.09	0.22	0.11	0.07	0.05	0.02	0.00	0.00	0.00	0.00	0.00
NTC	40	I	2.90	6.17	6.80	7.24	7.87	8.65	9.32	9.87	10.30	10.63	10.88	11.10	11.32	11.52
NTC	42	i	2.71	0.25	0.38	0.19	0.16	0.18	0.07	0.08	0.02	0.01	0.01	0.01	0.01	0.00
NTC	42	I	2.71	5.67	6.30	7.06	7.75	8.61	9.47	10.19	10.75	11.18	11.65	12.04	12.40	12.69

Plot	Biochar Rate	Biomass	Grain
1	5	0.78	346.2
1	5	1.05	459.3
2	25	0.78	269.9
2	25	0.62	231.4
3	0	0.68	201.6
3	0	0.54	185.2
4	0	0.56	202.4
4	0	0.69	206.7
5	5	0.76	232.9
5	5	0.81	303.8
6	25	0.71	251
6	25	1.4	444.5
7	0	0.76	274.7
7	0	0.73	280.5
8	5	0.67	225.8
8	5	0.8	287.1
9	0	0.65	196.5
9	0	0.71	307
10	25	0.89	323.4
10	25	0.73	272.5
11	25	0.87	259.7
11	25	0.71	230.2
12	5	0.84	358.2
12	5	0.92	325.5
13	25	0.79	300
13	25	0.94	400
14	25	0.93	373.8
14	25	0.85	304.4
15	5	0.67	255
15	5	0.81	350.8
16	0	0.94	403.7
16	0	0.79	293
17	5	0.85	323.85
17	5	0.93	394.2
18	0	0.59	233.4
18	0	0.78	328.4
19	5	0.9	366.3
19	5	0.98	440
20	5	0.98	378.4

20	5	0.58	241.1
21	25	1.05	461.5
21	25	0.89	353.3
22	0	0.68	256.9
22	0	0.89	355.8
23	0	0.8	300
23	0	0.62	216.8
24	25	0.76	320.9
24	25	0.81	289.6
25	0	0.62	240.9
25	0	0.66	238.1
26	5	0.88	345.6
26	5	0.6	232.2
27	5	0.66	241.2
27	5	0.79	310.5
28	25	0.86	331.6
28	25	0.82	258
29	0	0.76	243.3
29	0	0.77	287.9
30	25	0.83	301.1
30	25	0.96	354.9
31	0	0.78	323.2
31	0	0.94	408.3
32	0	0.74	272.5
32	0	0.77	310.5
33	25	0.85	323.4
33	25	0.75	274.1
34	5	0.69	282.9
34	5	0.67	268
35	25	0.78	277.7
35	25	0.46	181.7
36	5	0.65	241.7
36	5	0.59	196.2

Appendix B: Spring 2011 Data

Treatment	w	ρb'	ρb	θFC	θPWP	AWC	ft	fa
TB25	0.27	1.81	1.43	0.48	0.16	0.32	0.46	-0.02
TB25	0.26	1.86	1.47	0.49	0.16	0.33	0.45	-0.04
TB25	0.26	1.71	1.36	0.45	0.15	0.30	0.49	0.04
TB25	0.25	1.65	1.32	0.42	0.14	0.27	0.50	0.09
TB25	0.24	1.77	1.42	0.43	0.15	0.28	0.46	0.03
TB25	0.25	1.73	1.38	0.44	0.15	0.29	0.48	0.04
TB25	0.26	1.69	1.34	0.44	0.14	0.30	0.49	0.05
TB25	0.28	1.60	1.25	0.44	0.12	0.32	0.53	0.09
TB25	0.28	1.65	1.29	0.46	0.14	0.33	0.51	0.05
TB25	0.28	1.77	1.38	0.50	0.15	0.35	0.48	-0.02
TB25	0.25	1.76	1.40	0.44	0.15	0.29	0.47	0.03
TB25	0.28	1.72	1.34	0.49	0.14	0.35	0.50	0.01
TB25	0.27	1.45	1.14	0.39	0.12	0.27	0.57	0.18
TB25	0.27	1.64	1.29	0.45	0.15	0.30	0.51	0.07
TB25	0.30	1.69	1.30	0.51	0.15	0.36	0.51	0.00
TB25	0.27	1.76	1.38	0.48	0.16	0.32	0.48	0.00
TB25	0.29	1.62	1.26	0.47	0.15	0.33	0.52	0.05
TB25	0.25	1.45	1.16	0.36	0.13	0.23	0.56	0.20
TC	0.21	1.87	1.54	0.39	0.15	0.24	0.42	0.03
TC	0.21	1.81	1.49	0.39	0.15	0.24	0.44	0.05
TC	0.23	1.77	1.44	0.40	0.14	0.26	0.46	0.06
TC	0.24	1.80	1.46	0.43	0.14	0.29	0.45	0.02
TC	0.24	1.63	1.31	0.40	0.12	0.28	0.51	0.11
TC	0.24	1.86	1.50	0.45	0.14	0.31	0.43	-0.02
TC	0.24	1.84	1.49	0.44	0.15	0.28	0.44	0.00
TC	0.25	1.70	1.37	0.42	0.14	0.28	0.48	0.07
TC	0.22	1.92	1.57	0.42	0.16	0.26	0.41	-0.02
TC	0.26	1.88	1.49	0.49	0.16	0.33	0.44	-0.06
TC	0.27	1.76	1.38	0.48	0.16	0.32	0.48	0.00
TC	0.26	1.75	1.38	0.46	0.12	0.34	0.48	0.02
TC	0.23	1.63	1.32	0.38	0.13	0.24	0.50	0.12
TC	0.25	1.60	1.28	0.40	0.13	0.27	0.52	0.12
TC	0.23	1.59	1.29	0.37	0.13	0.24	0.51	0.14
TC	0.22	1.77	1.44	0.40	0.15	0.25	0.46	0.06
TC	0.25	1.76	1.41	0.44	0.16	0.28	0.47	0.03
TC	0.24	1.59	1.28	0.38	0.13	0.25	0.52	0.13
NTC	0.20	1.90	1.59	0.37	0.15	0.22	0.40	0.03

NTC	0.21	1.82	1.50	0.39	0.15	0.24	0.43	0.04
NTC	0.22	1.76	1.45	0.38	0.14	0.24	0.45	0.08
NTC	0.18	1.76	1.50	0.31	0.14	0.17	0.44	0.13
NTC	0.21	1.81	1.50	0.38	0.14	0.24	0.44	0.06
NTC	0.20	1.91	1.59	0.39	0.15	0.24	0.40	0.01

Treatment	5	2	1	0.5	0.25	TWSA	GMD	MWD	MWDc
TB25	13	6	6	12	11	48	1.19	1.23	1.00
TB25	4	6	6	11	11	38	1.04	0.66	0.50
TB25	8	5	6	9	13	40	1.08	0.86	0.67
TB25	19	5	6	17	17	64	1.16	1.66	1.38
TB25	17	5	6	11	14	53	1.21	1.49	1.23
TB25	24	4	5	12	15	61	1.27	1.90	1.59
TB25	8	4	6	12	13	42	1.08	0.89	0.70
TB25	7	3	8	18	18	54	0.97	0.85	0.67
TB25	6	5	4	16	22	53	0.93	0.80	0.62
TB25	15	7	5	12	17	56	1.16	1.45	1.19
TB25	25	5	5	10	12	57	1.36	1.99	1.66
TB25	17	3	7	16	18	60	1.11	1.45	1.19
TB25	10	6	6	7	7	35	1.26	0.97	0.77
TB25	24	2	5	7	11	49	1.39	1.79	1.49
TB25	17	3	6	7	10	43	1.29	1.36	1.12
TB25	7	7	6	9	13	41	1.09	0.86	0.68
TB25	19	7	5	8	13	53	1.29	1.64	1.36
TB25	30	3	4	8	11	57	1.45	2.19	1.84
TC	26	3	5	8	12	55	1.37	1.96	1.64
TC	11	7	6	9	14	47	1.14	1.14	0.92
TC	18	6	6	9	13	51	1.26	1.51	1.25
TC	5	5	5	8	11	35	1.07	0.70	0.53
TC	5	5	6	11	16	43	0.98	0.70	0.54
TC	8	5	6	14	13	45	1.06	0.90	0.71
TC	19	6	6	11	16	58	1.21	1.64	1.36
TC	21	4	7	12	15	59	1.24	1.73	1.43
TC	23	7	6	12	16	65	1.27	1.99	1.66
TC	8	7	8	17	14	54	1.05	1.01	0.81
TC	10	5	8	14	18	56	1.05	1.13	0.91
TC	11	6	11	22	16	65	1.06	1.25	1.02

TC	9	6	8	16	20	58	1.02	1.06	0.85
TC	9	4	8	18	20	59	1.00	1.03	0.83
TC	8	6	10	22	16	62	1.03	1.09	0.88
TC	19	6	8	15	14	61	1.21	1.66	1.38
TC	12	8	8	15	18	61	1.10	1.35	1.11
TC	19	7	8	13	16	63	1.21	1.72	1.43
NTC	21	5	9	15	19	69	1.16	1.79	1.49
NTC	30	5	6	12	15	67	1.34	2.30	1.94
NTC	25	6	7	13	16	68	1.26	2.06	1.72
NTC	15	5	8	15	18	61	1.10	1.40	1.15
NTC	8	8	9	18	20	63	1.03	1.12	0.91
NTC	7	8	9	15	19	58	1.02	1.04	0.83

Treatment	Ks1	Ks2	Ks3	Ks4
TB25	4.1	3.5	3.3	3.0
TB25	1.9	0.9	0.9	0.9
TB25	47.4	50.4	50.9	46.9
TB25	222.4	182.3	157.0	134.0
TB25	167.1	147.7	136.4	124.1
TB25	173.1	146.3	120.8	116.4
TB25	65.1	55.8	48.9	41.5
TB25	80.5	75.5	66.8	63.8
TB25	20.5	12.7	11.7	.
TB25	13.7	11.6	9.3	8.6
TB25	101.9	92.8	86.6	74.8
TB25	6.7	5.7	5.2	12.0
TB25	253.5	201.2	205.4	186.7
TB25	215.4	176.5	153.0	133.2
TB25	15.8	10.5	9.5	.
TB25	87.8	96.8	126.0	103.1
TB25	110.6	100.4	122.6	86.0
TB25	356.5	251.4	197.6	175.2
TC	9.8	8.6	8.4	8.1
TC	28.5	24.4	20.8	16.7
TC	30.0	25.7	24.7	9.1
TC	8.5	32.0	77.1	91.1
TC	70.4	72.4	67.3	61.7

TC	209.8	197.5	183.9	170.8
TC	8.0	7.3	6.8	6.6
TC	83.4	75.6	66.0	68.1
TC	9.1	7.9	7.4	7.7
TC	111.3	107.5	98.0	93.4
TC	100.9	109.3	102.5	99.4
TC	35.2	39.6	37.5	36.4
TC	36.4	34.5	32.4	29.7
TC	36.5	32.1	30.2	28.0
TC	124.2	114.2	102.4	88.8
TC	29.5	26.0	23.2	22.3
TC	12.3	11.3	10.9	10.3
TC	320.8	283.5	273.0	263.0
NTC	5.7	5.2	5.0	4.8
NTC	13.0	10.8	9.8	8.1
NTC	110.1	101.6	98.5	91.5
NTC	84.1	72.2	70.1	61.0
NTC	22.6	15.9	14.4	13.4
NTC	8.7	7.3	6.1	4.8

Treatment	0	0.001	0.003	0.006	0.033	0.1	0.3	1.5
TB25	0.48	0.43	0.41	0.40	0.35	0.34	0.32	0.16
TB25	0.46	0.42	0.41	0.39	0.35	0.33	0.31	0.16
TB25	0.49	0.41	0.38	0.37	0.32	0.30	0.27	0.15
TB25	0.48	0.42	0.38	0.36	0.31	0.29	0.27	0.14
TB25	0.50	0.44	0.41	0.39	0.34	0.32	0.31	0.15
TB25	0.49	0.43	0.40	0.39	0.34	0.31	0.30	0.15
TB25	0.52	0.44	0.39	0.37	0.32	0.30	0.28	0.14
TB25	0.52	0.42	0.38	0.36	0.31	0.29	0.27	0.12
TB25	0.49	0.43	0.39	0.37	0.32	0.30	0.27	0.14
TB25	0.48	0.41	0.38	0.37	0.32	0.30	0.28	0.15
TB25	0.52	0.45	0.42	0.40	0.35	0.33	0.31	0.15
TB25	0.52	0.46	0.43	0.41	0.36	0.34	0.32	0.14
TB25	0.51	0.40	0.37	0.35	0.31	0.29	0.27	0.12
TB25	0.54	0.44	0.41	0.39	0.35	0.33	0.29	0.15
TB25	0.51	0.45	0.42	0.41	0.38	0.37	0.35	0.15
TB25	0.52	0.44	0.41	0.40	0.35	0.33	0.31	0.16

TB25	0.52	0.44	0.41	0.39	0.35	0.33	0.31	0.15
TB25	0.55	0.42	0.39	0.37	0.32	0.30	0.28	0.13
TC	0.49	0.44	0.39	0.38	0.32	0.30	0.28	0.15
TC	0.51	0.44	0.41	0.39	0.35	0.33	0.31	0.15
TC	0.48	0.40	0.37	0.35	0.30	0.28	0.26	0.14
TC	0.46	0.41	0.39	0.37	0.33	0.30	0.28	0.14
TC	0.50	0.41	0.36	0.34	0.29	0.27	0.25	0.12
TC	0.46	0.42	0.39	0.37	0.32	0.29	0.26	0.14
TC	0.49	0.43	0.40	0.38	0.34	0.32	0.30	0.15
TC	0.52	0.44	0.39	0.37	0.32	0.29	0.26	0.14
TC	0.45	0.41	0.40	0.39	0.35	0.33	0.30	0.16
TC	0.48	0.43	0.41	0.39	0.36	0.33	0.31	0.16
TC	0.49	0.43	0.40	0.39	0.34	0.32	0.30	0.16
TC	0.47	0.40	0.37	0.36	0.31	0.29	0.27	0.12
TC	0.48	0.40	0.37	0.35	0.30	0.28	0.26	0.13
TC	0.48	0.41	0.36	0.34	0.28	0.26	0.24	0.13
TC	0.46	0.38	0.35	0.33	0.29	0.26	0.25	0.13
TC	0.49	0.43	0.40	0.38	0.33	0.30	0.27	0.15
TC	0.45	0.39	0.37	0.35	0.31	0.29	0.27	0.16
TC	0.43	0.35	0.32	0.30	0.26	0.24	0.22	0.13
NTC	0.44	0.40	0.38	0.37	0.33	0.31	0.29	0.15
NTC	0.45	0.40	0.37	0.36	0.32	0.30	0.29	0.15
NTC	0.46	0.38	0.36	0.34	0.30	0.28	0.25	0.14
NTC	0.46	0.40	0.37	0.35	0.31	0.29	0.26	0.14
NTC	0.44	0.39	0.37	0.35	0.31	0.29	0.26	0.14
NTC	0.43	0.39	0.37	0.35	0.31	0.29	0.26	0.15

Treatment	1500	150	50	25	4.5	1.5	0.5	0.1
TB25	17.80	5.30	4.08	14.60	4.31	5.19	54.51	52.26
TB25	14.71	4.75	3.78	15.60	5.74	6.06	49.85	53.85
TB25	28.00	9.38	4.82	16.90	7.26	7.37	41.74	50.96
TB25	22.56	12.16	6.30	16.53	6.30	7.19	42.64	47.78
TB25	21.65	9.36	5.55	16.00	5.49	6.52	50.63	49.69
TB25	18.75	8.75	5.01	16.79	6.89	6.12	47.12	49.70
TB25	27.43	14.93	6.39	16.68	6.84	6.31	47.88	47.31
TB25	34.83	13.47	5.89	16.19	6.63	7.15	48.58	40.78
TB25	20.57	14.42	6.62	17.30	4.96	8.87	46.14	45.87

TB25	23.68	9.92	5.07	15.26	6.77	7.38	46.34	50.37
TB25	22.92	9.14	5.44	16.62	6.73	7.79	52.02	49.81
TB25	19.76	8.57	6.18	16.50	6.22	6.42	60.51	47.55
TB25	36.86	9.81	5.65	14.55	5.75	5.61	50.06	40.21
TB25	31.69	10.13	5.79	15.13	6.69	10.47	47.09	48.10
TB25	17.69	9.84	3.70	10.45	5.10	6.25	65.90	50.05
TB25	29.33	7.90	4.56	14.00	7.83	6.30	50.26	52.53
TB25	29.33	8.91	5.32	15.22	6.09	3.95	55.55	47.76
TB25	38.87	12.50	5.29	14.19	7.23	8.11	48.25	40.18
TC	19.45	13.56	6.29	17.37	6.78	6.24	42.77	50.40
TC	24.05	10.49	5.06	14.44	5.94	5.53	53.23	47.52
TC	29.05	10.21	5.15	16.89	8.33	5.81	39.68	47.26
TC	15.83	8.93	5.81	14.47	7.98	7.35	47.74	45.11
TC	29.77	14.98	7.22	15.33	6.93	6.20	43.79	39.91
TC	13.64	10.95	6.93	16.29	8.71	10.56	39.89	46.70
TC	20.07	10.77	7.06	12.80	6.34	5.61	50.15	51.49
TC	26.94	16.15	8.08	16.22	9.14	8.49	40.26	46.44
TC	12.83	4.16	3.41	11.27	8.46	8.72	46.08	52.40
TC	17.78	5.89	4.55	12.60	8.36	8.30	46.75	54.59
TC	20.38	6.68	5.61	14.58	8.85	6.60	46.66	51.13
TC	25.05	8.29	5.81	15.16	7.95	4.70	50.58	41.36
TC	27.24	11.12	6.89	15.01	6.83	6.25	42.54	43.96
TC	22.69	16.81	8.67	17.37	9.37	7.18	35.39	44.00
TC	26.91	11.44	6.38	13.87	7.31	6.09	38.25	42.77
TC	20.46	9.00	6.06	15.21	9.12	9.30	42.03	47.08
TC	18.01	7.13	5.09	13.37	6.77	8.46	36.93	52.16
TC	26.85	10.43	5.87	14.28	7.80	6.68	29.52	43.44
NTC	12.33	5.47	3.95	12.93	6.90	5.70	45.49	49.96
NTC	19.00	8.06	5.01	12.72	5.46	3.69	46.49	49.03
NTC	24.29	9.01	5.40	13.19	8.01	8.23	37.94	44.80
NTC	19.23	9.76	5.41	13.21	8.21	7.85	38.46	45.02
NTC	14.45	7.60	5.54	14.48	7.19	8.29	40.02	46.24
NTC	14.27	7.05	4.54	13.54	8.01	8.19	38.13	49.02

Treatment	Size	TS	Treatment	Size	TS	Treatment	Size	TS
BO	Large	1.46	SBO	Large	0.30	BF3	Large	0.43
BO	Large	2.27	SBO	Large	1.98	BF3	Large	0.52

BO	Large	0.53	SBO	Large	0.55	BF3	Large	0.76
BO	Large	1.59	SBO	Large	1.16	BF3	Large	0.58
BO	Large	0.81	SBO	Large	0.66	BF3	Large	0.41
BO	Large	0.31	SBO	Large	1.66	BF3	Large	0.54
BO	Large	0.45	SBO	Large	1.01	BF3	Large	0.80
BO	Large	1.39	SBO	Large	0.72	BF3	Large	0.73
BO	Large	0.66	SBO	Large	0.52	BF3	Large	0.64
BO	Large	1.88	SBO	Large	0.89	BF3	Large	0.64
BO	Large	0.95	SBO	Large	0.43	BF3	Large	0.45
BO	Large	0.55	SBO	Large	0.47	BF3	Large	0.81
BO	Large	0.90	SBO	Large	0.43	BF3	Large	0.35
BO	Large	1.23	SBO	Large	2.04	BF3	Large	0.41
BO	Large	1.58	SBO	Large	5.86	BF3	Large	0.49
BO	Large	1.11	SBO	Large	0.66	BF3	Large	0.86
BO	Large	1.31	SBO	Medium	0.95	BF3	Large	0.57
BO	Large	0.80	SBO	Medium	0.84	BF3	Large	1.10
BO	Large	0.47	SBO	Medium	0.63	BF3	Large	0.78
BO	Large	1.85	SBO	Medium	3.46	BF3	Medium	0.82
BO	Medium	0.48	SBO	Medium	0.73	BF3	Medium	1.36
BO	Medium	2.24	SBO	Medium	0.50	BF3	Medium	0.37
BO	Medium	0.49	SBO	Medium	0.82	BF3	Medium	0.63
BO	Medium	2.46	SBO	Medium	0.45	BF3	Medium	0.56
BO	Medium	2.45	SBO	Medium	1.40	BF3	Medium	0.71
BO	Medium	0.93	SBO	Medium	0.61	BF3	Medium	0.49
BO	Medium	1.00	SBO	Medium	0.71	BF3	Medium	0.32
BO	Medium	1.04	SBO	Medium	1.25	BF3	Medium	0.19
BO	Medium	0.90	SBO	Medium	0.63	BF3	Medium	0.35
BO	Medium	0.77	SBO	Medium	0.51	BF3	Medium	0.23
BO	Medium	0.39	SBO	Medium	0.45	BF3	Medium	0.31
BO	Medium	1.96	SBO	Medium	1.70	BF3	Medium	0.86
BO	Medium	1.20	SBO	Medium	0.79	BF3	Medium	0.93
BO	Medium	0.36	SBO	Medium	2.30	BF3	Medium	0.93
BO	Medium	0.90	SBO	Medium	1.13	BF3	Medium	0.31
BO	Medium	1.07	SBO	Small	2.59	BF3	Medium	0.73
BO	Medium	0.76	SBO	Small	1.47	BF3	Medium	0.51
BO	Medium	0.53	SBO	Small	0.66	BF3	Small	0.82
BO	Medium	0.48	SBO	Small	0.93	BF3	Small	1.85
BO	Medium	0.38	SBO	Small	1.18	BF3	Small	0.58

BO	Medium	0.87	SBO	Small	0.52	BF3	Small	0.26
BO	Medium	0.74	SBO	Small	1.25	BF3	Small	0.75
BO	Medium	0.62	SBO	Small	1.38	BF3	Small	0.30
BO	Small	1.08	SBO	Small	1.52	BF3	Small	1.20
BO	Small	1.16	SBO	Small	1.46	BF3	Small	0.46
BO	Small	1.28	SBO	Small	1.31	BF3	Small	0.40
BO	Small	1.30	SBO	Small	0.96	BF3	Small	1.31
BO	Small	0.87	SBO	Small	1.06	BF3	Small	0.69
BO	Small	1.28	SBO	Small	1.09	BF3	Small	0.54
BO	Small	3.67	SBO	Small	0.81	BF3	Small	0.49
BO	Small	1.13	SBO	Small	0.57	BF3	Small	0.74
BO	Small	1.60	SBO	Small	2.82	BF3	Small	0.95
BO	Small	0.45	SBO	Small	0.84			
BO	Small	0.94	SBO	Small	1.85			
BO	Small	0.92						
BO	Small	1.35						
BO	Small	0.60						
BO	Small	0.94						
BO	Small	0.69						
BO	Small	1.56						
BO	Small	2.50						
BO	Small	0.72						
BO	Small	1.64						
BO	Small	1.79						
BO	Small	0.75						
BO	Small	0.50						

Treatment	TM	8	4.75	2	1	0.5	0.25	0
BO	53.88	15.17	27.81	10.54	0.01	0.02	0.01	0.32
BO	51.93	12.5	22.89	16.08	0.21	0.03	0.04	0.18
BO	60.96	9.52	24.91	25.93	0.34	0.01	0.01	0.24
BF3	60.8	6.61	23.17	23.17	5.36	1.5	0.45	0.5
BF3	59.5	7.92	19.23	25.17	4.89	1.43	0.32	0.5
BF3	66.6	11.11	24.02	27.81	2.5	0.71	0.23	0.2
BF6	76.4	6.2	15.83	32.53	15.1	4.87	0.88	1.0
BF6	60.4	6.21	11.72	21.53	13.6	5.45	1.15	0.8
BF6	66.7	4.89	15.46	30.02	10.86	3.97	0.9	0.6

BF9	58.2	1.53	8.6	21.95	16.8	6.99	1.32	1.0
BF9	60.2	3.38	7.99	21.63	17.83	7.03	1.45	0.9
BF9	61.2	1.76	7.2	21.06	19.01	9.24	1.93	1.0

Biochar (g)	Mass_Ratio	Volume_Ratio	Biomass	Grain	W	pb	theta	AWC	ft	fa	Ks3
0.75	0.002	0.004	7800	2699	0.27	1.43	0.48	0.32	0.46	-0.02	3.3
0.81	0.002	0.004	7300	2758.5	0.24	1.36	0.40	.	0.49	0.09	25.2
1.08	0.002	0.005	7800	3097.5	0.22	1.48	0.40	.	0.44	0.04	14.4
1.18	0.003	0.005	6900	2829	0.25	1.39	0.43	.	0.47	0.05	12.8
3.07	0.006	0.014	6200	2314	0.26	1.47	0.49	0.33	0.45	-0.04	0.9
3.86	0.008	0.018	7800	2777	0.26	1.36	0.45	0.30	0.49	0.04	50.9
4.23	0.010	0.020	8900	3234	0.25	1.32	0.42	0.27	0.50	0.09	157.0
4.63	0.010	0.022			0.24	1.42	0.43	0.28	0.46	0.03	136.4
5.51	0.012	0.026			0.25	1.38	0.44	0.29	0.48	0.04	120.8
6.31	0.014	0.029			0.26	1.34	0.44	0.30	0.49	0.05	48.9
7.01	0.017	0.033			0.28	1.25	0.44	0.32	0.53	0.09	66.8
7.2	0.017	0.034			0.28	1.29	0.46	0.33	0.51	0.05	11.7
7.61	0.016	0.035	8600	3316	0.28	1.38	0.50	0.35	0.48	-0.02	9.3
7.98	0.019	0.036	8500	3234	0.30	1.21	0.48	.	0.54	0.06	58.3
9.63	0.021	0.046	7300	2725	0.25	1.40	0.44	0.29	0.47	0.03	86.6
9.86	0.022	0.046			0.28	1.34	0.49	0.35	0.50	0.01	5.2
9.88	0.026	0.047	8900	3533	0.27	1.14	0.39	0.27	0.57	0.18	205.4
11.67	0.028	0.056			0.27	1.29	0.45	0.30	0.51	0.07	153.0
12.9	0.030	0.061			0.30	1.30	0.51	0.36	0.51	0.00	9.5
13.36	0.029	0.063	7900	3000	0.27	1.38	0.48	0.32	0.48	0.00	126.0
15.17	0.033	0.074	8200	2580	0.25	1.41	0.45	.	0.47	0.02	128.3
16.21	0.039	0.077	9400	4000	0.29	1.26	0.47	0.33	0.52	0.05	122.6
24.39	0.066	0.119	4600	1817	0.25	1.16	0.36	0.23	0.56	0.20	197.6