The Influence of Wood-Derived Biochar on Physico-Mechanical and Hydraulic Characteristics of Agricultural Soils: Implications for Machine–Soil Interactions and Carbon Sequestration

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Abstract

Biochar has gained research interest because of its high pore volume and adsorption capacity when applied as an agricultural soil amendment because of its ability to enhance soil nutrient and water holding capacities. In addition to increasing soil quality, biochar amendments sequester carbon within the soil. In most applications, crop productivity significantly increases after agricultural soils are amended with biochar. However, the mechanisms behind this increase are not fully understood, nor is the influence of biochar on soil compaction. Therefore, this laboratory study focuses on the influences of wood-derived biochar (WBC) on the physico-mechanical properties of agricultural soils prone to compaction.

First, a screening study was carried out to assess the changes in the physico-mechanical properties of a silt loam (STL) soil amended with WBC. The amended soil was more susceptible to compaction due to the increase in plasticity and optimum moisture content; however, the soil mechanical impedance was enhanced by lower penetration resistance and shear strength. The next step was to investigate the influence on the compaction, workability and fertility of two texturally contrasting agricultural soils of WBC amendments of two particle size ranges. Although the clay loam (CL) soil workability decreased with relatively coarser WBC partcle size, soil fertility was not enhanced.

The effects of WBC application on the hydraulic characteristics of compacted CL and sandy loam (SL) soils were also investigated. Results showed that the saturated hydraulic conductivity of the amended SL soil decreased while in the amended CL soil, the trend was reversed. Further, the water holding capacities of the SL soils increased with 10% amendment of 0.5–420 μm particle size WBC. Further, the soil pore size distribution of the treatments was determined from the soil water retention curves (SWRCs). An increase in the capillary pores was not observed at any WBC

amendment level. Alternatively, an increase in the transmission and storage pores were observed when 10% 0.5–420 μm particle size WBC was applied to the CL soil.

A simulation scenario was carried out with a crop simulation model to determine the potential of sequestering carbon in simulated agricultural fields due to changes in soil physical properties. Simulated results indicated that if the hydraulic characteristics and density were enhanced in SL and CL samples based on finding from this study, a net negative carbon emission (carbon sequestration in soil) of 13.3% and 12%, respectively, would be induced.

The main goal of the next study component was to investigate the influence of WBC amendment strength upon compaction for SL and CL soils, which exhibit contrasting behavior in terms of shear parameters. Moreover, the soil consistency limits could predict the compacted soil strength. In order to theoretically investigate the influence of WBC amendment on the tillage power requirements associated with changes in soil properties, models from the literature were employed to determine the soil failure in front of a tillage tool, tillage draft, and tractor thrust. Amendment of WBC with a particle size range of 0.5–420 μm decreased tillage power requirements in the CL soil and increased tillage power requirements in the SL soil.

Résumé

L'intérêt croissant porté aux recherches sur le biocharbon est lié a son volume poreux et sa capacité d'adsorption élevés, et le fait que, lorsqu'épandu sur un sol agricole comme amendement, il en améliore la capacité de rétention des éléments nutritifs et de l'eau. En plus d'améliorer la qualité du sol, les amendements de biocharbon séquestrent le carbone dans le sol. Dans la majorité des cas où un sol agricole reçoit un amendement en biocharbon, la productivité des cultures est améliorée. Cependant, les mécanismes à l'origine de cette amélioration ne sont pas entièrement compris, tout comme ceux qui contribuent à l'effet du biocharbon sur le compactage du sol. Cette étude en laboratoire s'adresse donc particulièrement aux l'influences de biocharbon issu de bois (BIB) sur les propriétés physico-mécaniques des sols agricoles susceptibles au compactage.

Comme première étape, une étude de dépistage fut entreprise pour évaluer les changements provoqués par l'amendement d'un loam limoneux avec du biocharbon. Le sol amendé s'avéra plus susceptible au compactage de par une augmentation de sa plasticité et de sa teneur en humidité optimale. Cependant, l'impédance mécanique du sol fut améliorée par la diminution de sa résistance à la pénétration ainsi que sa résistance au cisaillement.

La prochaine étape visa à évaluer l'influence d'amendements de biocharbon de deux plages de taille de particules différentes sur la fertilité de deux sols aux textures contrastantes. Pour un loam argileux la maniabilité du sol fut réduite, tandis que sa fertilité demeura la même.

L'étude suivante évalua l'influence d'un amendement en biocharbon sur la résistance d'un loam argileux et d'un limon-sableux après compactage. Lorsqu'amendés avec du biocharbon, ces sols présentèrent des types de comportement opposés quant à leurs paramètres de résistance au cisaillement. De plus, les limites de consistance des sols permirent de prédire la résistance des sols compactés. Afin d'entreprendre une enquête théorique sur l'influence des changements en propriétés du sol suivant un amendement en biocharbon sur les besoins de puissance pour le travail du sol, des modélisations issues de la litérature furent employées pour calculer la rupture du sol s'opérant selon l'outil de travail du sol, l'effort du travail du sol, et la poussée du tracteur. Un amendement de BIB ayant une gamme de diamètres de particule de 0.5 à 420 µm ($PS_{1,2}$) diminua l'effort du travail du loam argileux mais augmenta celui du limon-sableux.

Les effets sur le comportement hydraulique du loam argileux et du limon-sableux ayant reçu un amendement de BIB et subi un compactage furent également évalués. Un amendement en BIB diminua la conductivité hydraulique en milieu saturé du limon-sableux ($p < 0.05$), mais augmenta celui du loam argileux. Par ailleurs, la capacité de rétention d'eau des deux sols fut augmentée par un amendement de $PS_{1,2}$ à 10%. La distribution de la taille des pores des sols amendés fut calculée à partir des courbes de rétention d'eau préparées pour ces sols. Aucun taux d'amendement en BIB des sols n'eut un effet sur le nombre de pores capillaires (<0.2 µm). Par contre, un amendement de $PS_{1,2}$ à 10% au loam argileux augmenta ($p < 0.05$) le nombre de pores de transmission (30-60 µm) et de stockage (0.2- 60 µm).

Un modèle de simulation de culture a permis de simuler un scénario d'amendement en BIB d'un sol agricole afin d'évaluer le potentiel de piégeage de carbone qu'il offre, selon les altérations des propriétés physiques des sols qui s'en suivent. Les résultats de ces simulations indiquèrent que pour un champ avec un loam argileux l'amélioration des caractéristiques hydrauliques et de la densité apparente du sol seraient suffisantes pour induire une émission nette négative de 0.02 Mg ha^{-1} an^{-1}.

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Format of Thesis

This thesis is submitted in the format of papers suitable for journal publication that follows the "Guidelines for Thesis Preparation", Faculty of Graduate and Postdoctoral Studies, McGill University as follows:

"Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly-duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis).

2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.

3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following:

(a) A table of contents;

(b) An abstract in English and French;

(c) An introduction which states the rationale and objectives of the research;

(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper);

(e) A conclusion and summary;

4. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g., in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

5. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this statement at the doctoral oral defense. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the co-authored papers"

Contribution of Authors

The research work reported in this thesis was conducted by Mr. Ahmed S. Ahmed at the Department of Bioresource Engineering, McGill University. He was responsible for conceptualization, design, and execution of the experiments, analysis of the results, and preparation of manuscripts under the supervision of Prof. G. S. Vijaya Raghavan, Department of Bioresource Engineering, McGill University. Mr. Yvan Gariépy Department of Bioresource Engineering, McGill University, provided technical support and information for most of the experimental work. Dr. Jiby Kudakasseril Kurian at the Department of Bioresource Engineering, McGill University, assisted Ahmed S. Ahmed in the review of the literature and analyzing the results for the carbon sequestration method in Chapter VII, along with Dr. Sri Sathyanarayanan. Mr. Sai Kranthi Vanga assisted Ahmed S. Ahmed in the global bibliometric analysis review paper. The following articles are published, have been accpeted or submitted for peer review based on this thesis:

1) Ahmed A., Sai K. Vanga, and G.S. Vijaya Raghavan (2017). A global bibliometric analysis of the research in biochar. *Journal of Agricultural & Food Information,* available online (https://doi.org/10.1080/10496505.2017.1403328).
2) Ahmed A., Kurian J., and G.S. Vijaya Raghavan (2016). Influence of biochar on agricultural soils, crop production and the environment – A review. *Environmental Reviews,* 24(4): 495–502.
3) Ahmed A., Gariepy Y., and G.S. Vijaya Raghavan (2017). Influence of wood-derived biochar on the compactibility and strength of silt loam soil. *International Agrophysics,* 31(2): 149–155.
4) Ahmed A., and G.S. Vijaya Raghavan (2017). Influence of wood-derived biochar particle size on the physico-mechanical and chemical characteristics of two texturally contrasting agricultural soils. *International Agrophysics,* 32(1), 1–10.

5) Ahmed A., Kurian j., Sri S., and G. S. Vijaya Raghavan (2018). The impact of wood-derived biochar on the hydraulic characteristics of two texturally contrasting compacted agricultural soils: Its implications on carbon sequestration. *(Accepted in Catena)*.

6) Ahmed A., and G.S. Vijaya Raghavan (2018). Influence of wood-derived biochar particle sizes on the strength along the compaction curve of two texturally contrasting compacted agricultural soils: Its implications on tillage requirements. (Submitted to the *Journal of Terramechanics*).

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Acronyms and Symbols

5B	5 rammer blows
10B	10 rammer blows
15B	15 rammer blows
25B	25 rammer blows
ϕ	Angle of Internal friction (º)
AWC	Available water capacity (%)
ρ	Bulk density (t/m^3)
CEC	Cation exchange capacity
CL	Clay loam
tan ϕ	Coefficient of internal friction (dimensionless)
c	Cohesion (kPa)
D_{pull}	Drawbar pull (kN)
FC	Field capacity (%)
FI	Friability index
θ_{ll}	Liquid limit (%)
ρ_o	Loose bulk density (t/m^3)
h	Matric potential (hydraulic head)
ρ_{max}	Maximum bulk density (t/m^3)
τ_{max}	Maximum shear along the compaction curve (kPa)
d	Mean aggregate diameter (m)
MR	Motion resistance (kN)
θ_{opt}	Optimum moisture content for maximum Proctor compaction (%)
θ_{till}	Optimum moisture content for tillage (%)

OM	Organic matter
Q_p	Overburden pressure (kPa)
PR	Penetration resistance (kPa)
PWP	Permanent wilting point (%)
θ_{pl}	Plastic limit (%)
PI	Plasticity index (%)
F	Polar force needed to fracture a soil aggregate (N)
P_{req}	Power required to pull a tillage tool (hp)
r	Rate of increase in τ_{max} with P_c
RBD	Relative bulk density (%)
RID	Relative increase in bulk density from loose dry to maximum Proctor (%)
SL	Sandy loam
k_{sat}	Saturated hydraulic conductivity (mm/h)
τ	Shear strength (kPa)
STL	Silt loam
SWRC	Soil water retention charactaristic curve
G_s	Specific Gravity (dimensionless)
P_c	Static pressure equivalence to compaction rammer blows (kPa)
σ_t	Tensile strength (kPa)
T	Tractor's thrust (kN)
TP	Transmission pore
k_{unsat}	Unsaturated hydraulic conductivity (mm/h)
a_o	Value of τ_{max} at zero P_c

θ	Water content (Gravimetric-dry basis) (%)
v	Water content (Volumetric)
WHC	Water-holding capacity
WBC	Wood-derived biochar
PS_1	WBC with particle size range 0.5–210 µm (passing sieve 70)
PS_2	WBC with particle size range 210–420 µm (retained between sieve 40 - 70)
$PS_{1,2}$	WBC with particle size range 0.5–420 µm (Passing sieve 40)
PS_3	WBC with particle size range 420–841 µm (retained between sieve 20 - 40)
W_{till}	Workability moisture content for tillage (%)
W_{agg}	Workability of soil aggregates

Chapter I
General Introduction

Biochar is charcoal produced through pyrolysis or gasification of biomass under anaerobic conditions. The high pore volume, adsorption capacity, and ability to enhance soil nutrient- and water-holding capacity (WHC) of biochar have made it a focus of research interest within the agricultural and bioresources engineering research community. Soil amendment with biochar is considered as a method to both build the soil organic fraction and sequester carbon. In most applications, crop productivity is significantly increased after agricultural soils are amended with biochar; however, the full effects of these amendments are difficult to predict since the mechanisms behind the productivity increase are not yet fully elucidated. Therefore, researchers around the world are striving to investigate the overall effect of biochar on soils, plants, and the environment. While more than 2500 articles on biochar were published between 2009 and 2015, very few were published prior to 2009. The growing interest in the recent years indicates that biochar amendment is likely to become a commonplace practice. However, as noted above, accurately predicting the overall behavior of biochar-amended agricultural soils remains a challenge. Given its chemically inert nature, biochar is virtually impossible to remove once applied to a soil. Accordingly, its impacts on a given type of soil should be carefully assessed before amendment. Further research is essential to accurately predict the potential of biochar as a widely-used agricultural amendment.

Problem Statement

Compaction of agricultural soils by heavy equipment during cultivation reduces soil porosity and degrades soil tilth. Most studies on the tilth of soil amended with biochar have focused on increases in crop yield, but the influence of biochar on the tilth of compacted soils has yet to be documented.

Accordingly, this study focuses on quantifying the effects of wood biochar (WBC) amendment and WBC particle size on key parameters of clayey- *vs.* sandy-textured compacted soils (e.g., strength, water flow, and retention). Experiments were conducted to quantify changes in soil physico-mechanical properties after addition of WBC particles to the soil matrix. Using soil characteristics measured before treatment, models from the literature were used to predict compaction state, pore size distribution, tillage requirements, and potential carbon sequestration of WBC-amended compacted soils.

Thesis Hypothesis

Depending on the unamended soil textural characteristics, applying WBC will have, according to the quantity and particle size of WBC in the soils, positive effects on the compacted soil's tilth (i.e., strength, water flow).

Research Objectives

The primary objective of this thesis was to elucidate: (i) the influence of WBC particles on the compacted agricultural soil matrix, and (ii) the environmental impact of biochar incorporation into agricultural fields.

Laboratory experiments were carried out with WBC-amended compacted soils to examine changes in soil physico-mechanical properties. Sandy loam (SL) and clay loam (CL) soils were used to investigate their physico-mechanical properties upon amendment with various WBC. The WBC used was produced by thermal decomposition (500°C) of forest wastes, fractionated into two particle size ranges 0.5–210 µm (PS_1), 210–420 µm (PS_2), 0.5–420 µm ($PS_{1,2}$), or 420–841 µm (PS_3). The maximum bulk density (ρ_{max}) and optimum moisture content (θ_{opt}) were determined through the standard Proctor compaction test. Soil consistency limits in terms of plastic limit (θ_{pl})

and liquid limit (θ_{ll}) were determined as the Atterberg limits. The penetration resistance (PR) of the compacted soils in the standard Proctor mold was determined by a penetrometer.

Models from the literature were employed to predict the effect of WBC on the experimental soil compaction state, pore size distribution and carbon sequestration. The Van Genuchten (1980) model was chosen to simulate the water flow process in the soil. The data from the water retention were fitted with the hydrologic software RETC. The Century-EPIC simulation software was employed to calculate the soil carbon (C) sequestration potential of the soils from C mineralization rates. The Ohu (1985) model for predicting PR in agricultural soils amended with varying compositions of organic matter (OM) and compacted in a Proctor mold was examined for its suitability with the compacted soil-WBC mixture. The Hettiaratchi and Reece (1967) and McKyes (1985) models were used to predict the soil failure.

Specific research objectives were to:

	Chapter(s)
• Describe the current state of knowledge regarding biochar and the problem of agricultural soil compaction	II, III
• Examine the influence of WBC particle size on the physico-mechanical characteristics of WBC-amended agricultural soils	V, VI
• Examine the strength and hydrological properties of compacted WBC-amended soils	VII, VIII
• Theoretically investigate the influence of WBC presence in soil on tillage requirements by employing soil failure models based on classical soil mechanics theories	VIII

• Theoretically investigate the potential to use WBC for carbon sequestration in the farmland by employing models from the literature	VII

Connecting Text

After identifying the key objectives of the study that will test the hypothesis, it was necessary to develop an overall understanding of the relevant knowledge available in the literature. Accordingly, **Chapter II** presents a thorough global bibliometric analysis highlighting global trends in various fields of biochar research.

Chapter II

Global Bibliometric Analysis of the Research on Biochar

Abstract

Global interest in studying biochar stems from its ability to sequester carbon (C) in soil and render nutrients and moisture more readily available to plant root systems. Therefore, a bibliometric analysis was conducted to investigate global scientific publications related to biochar research, providing insight into the number of articles published, journal platforms, subjects, citations, and overall trends. The primary databases employed were the *Web of Science* and *Science Citation Index*. A total of 1,697 articles published between 2000 and 2015 were evaluated. There is an exponential increase in the research of biochar worldwide. This systematic bibliometric analysis will assist research groups and individuals to understand global biochar research trends and focus future research. The influence of biochar on soils, plants, and the environment continues to require greater attention. In conclusion, new avenues of biochar research are opening at a rapid pace.

Keywords *Web of Science*, *Journal Citation Reports*, literature review, biochar, bibliometric analysis

Introduction

Biochar is produced by pyrolysis, whereby the decomposition of biomass occurs in the absence of oxygen at temperatures between 250 and 700°C (Yuan et al. 2014). Given its high pore volume and adsorption capacity, biochar can enhance soil nutrient- and WHCs when applied as an agricultural soil amendment (Andrenelli et al. 2016). Thus, biochar has become a focus of research interest. However, the long-term effects of amending agricultural soils with biochar are difficult to predict since the mechanisms driving the increase in productivity of biochar-amended soils are not yet fully elucidated (Woolf et al. 2010). Therefore, scientists around the world are striving to investigate the effect of biochar on soil, plants, and the environment.

Although several literature surveys have been conducted on biochar and its influence on ecosystems (e.g., Nguyen et al. 2017; Thines et al. 2017; Vithanage et al. 2016), a bibliometric analysis (BA) of the distribution patterns of research articles (Vanga et al. 2015) on biochar is essential to accurately predict the potential of biochar as an agricultural amendment. For example, a BA of works published in the *International Journal of Pest Management* between 2005 and 2014 (Kolle et al. 2015) found an increasing trend in research on pest management worldwide, and concluded that tomato and cotton crops garnered the most attention in terms of number of articles and citations.

Bibliometric mapping uses various visualization tools and techniques to graphically represent relationships between a particular paper and a topic area (Buter et al. 2006). Bibliometric maps have several main topical nodes. Additional sub-nodes are plotted around the main nodes, with links back to the central node. Sub-sub nodes can be added to any of the sub-nodes, and so on. For example, Ahmed and Raghavan (2013) constructed a bibliometric map of biochar research, with four main nodes: Biochar, Soil, Environment, and Crop Production. This map organized all *Web of Science* search results with "biochar*" in the title, from 2000 to 2012. The map presents research that has been done, opportunities for future research (areas with fewer clusters), and identifies topics yet to be addressed (blank spaces), thereby constituting a tool to identify research gaps for future investigations. Indeed, Ahmed and Raghavan (2013) highlighted several research gaps, including the effect of pyrolysis temperature on biochar hydrophobicity, and the effect of biochar amendment on soil tensile strength and tractor draught force. The mapped data inferred that active biochar research fields cluster around analytical investigations of biochar, whereas the application of biochar to soils receives less attention.

Accordingly, the present study objective was to apply BA to quantitatively and statistically analyze the distribution patterns of research articles in the field of biochar studies over the period of 2000–2015, thereby providing insight into research trends and direct future research opportunities.

Data Sources and Methodology

Data retrieved

Recognized as the most comprehensive, technical, and scientific literature indexing tool and covering a wide range of subjects, the *Web of Science* database was used as the data source. The impact factor of the journals evaluated was determined by the *Journal Citation Reports* (JCR) of the Institute for Scientific Information (Thomson Scientific, Philadelphia, PA, USA). Currently the JCR is operated by Clarivate Analytics (Boston, MA, USA). The JCR database was also used to obtain the number of subject categories in which biochar articles were published.

Data presented in this study were mined on February 8, 2016 using the search terms:

Title: (‘‘biochar*’’)

Refined by: [excluding] DOCUMENT TYPES: (MEETING ABSTRACT OR PROCEEDINGS PAPER OR REVIEW OR EDITORIAL OR BOOK OR NEWS OR CORRECTIONS OR LETTER)

Timespan: 2000–2015

This extracted 2,277 results, of which 1,697 articles were used. Discarded results comprised reviews (unlike the BA of Kim et al. 2016), abstracts, meeting reports, editorials, books, case reports, reference materials, patents, and unspecified documents.

Method of analysis

The BA quantified the number and subject of the articles, publication journal, year of publication, country of origin, and institutes participating in published papers. Country of origin was determined by using the location of the affiliation/university of at least one author after Li et al. (2009). Data for 2016 were ignored as the year was incomplete when this manuscript was developed.

Results

Trends associated with articles over the years 2000–2015.

From 2000 through 2004, the number of targets ranged from 0 to 2. Between 2005 and 2015, the number of publications increased dramatically. In particular, the number of articles rose over 100-fold in 2015 relative to 2008 (Figure II.1). Kim et al. (2016) found the same increasing trend in worldwide research on biochar.

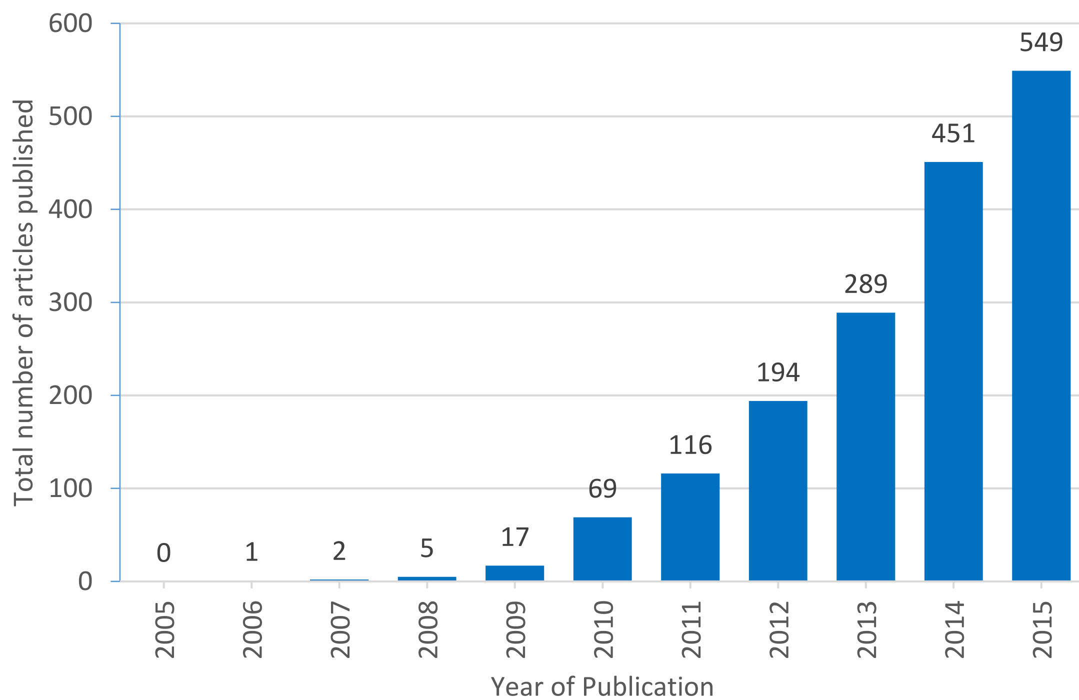

Figure II.1: Total number of biochar articles published each year between 2005 and 2015

Distribution of biochar articles based on journal and subject

Table II.1 shows the most cited articles in a given year. No relevant articles were published in 2001, 2002, or 2005, so these years are excluded. The journal *Environmental Science and Technology* published 28% of the most cited articles, followed by *Soil Biology and Biochemistry* (22%).

Table II.1: Number of biochar articles and most cited biochar articles between 2000 and 2015

Year	No. articles	Title of most cited article	Lead author, *Journal*	No. citations
2000	1	Biochar from the straw-stalk of rapeseed plant	Karaosmanoglu, *Fuels*	56
2003	1	A biochar from casein and its properties	Purevsuren, *J. Mat. Sci.*	16
2004	2	Production and characterization of bio-oil and biochar from rapeseed cake	Ozcimen, *Energy*	135
2006	1	Biochar as a precursor of activated carbon	Azargohar, *Ann. Biochem. Biotech.*	42
2007	2	Agronomic values of greenwaste biochar as a soil amendment	Chan, *Austral. J. Soil Res.*	357
2008	5	Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures	Chen, *Environ. Sci. Tech.*	275
2009	17	Impact of biochar amendment on fertility of a southeastern coastal plain soil	Novak, *Soil Sci.*	249
2010	69	Dynamic molecular structure of plant biomass-derived black carbon (biochar)	Keiluweit, *Environ. Sci. Tech.*	249
2011	116	Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	Zimmerman, *Soil Biol. Biochem.*	247
2012	194	Biochar-mediated changes in soil quality and plant growth in a three year field trial	Jones, *Soil Biol. Biochem.*	132
2013	289	Production of solid biochar fuel from waste biomass by hydrothermal carbonization	Liu, *Fuel*	67
2014	451	Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound-specific C-14 analysis	Kuzyakov, *Soil Biol. Biochem.*	31
2015	549	Removal of arsenic by magnetic biochar prepared from pinewood and natural hematite	Wang, *Biores. Tech.*	12

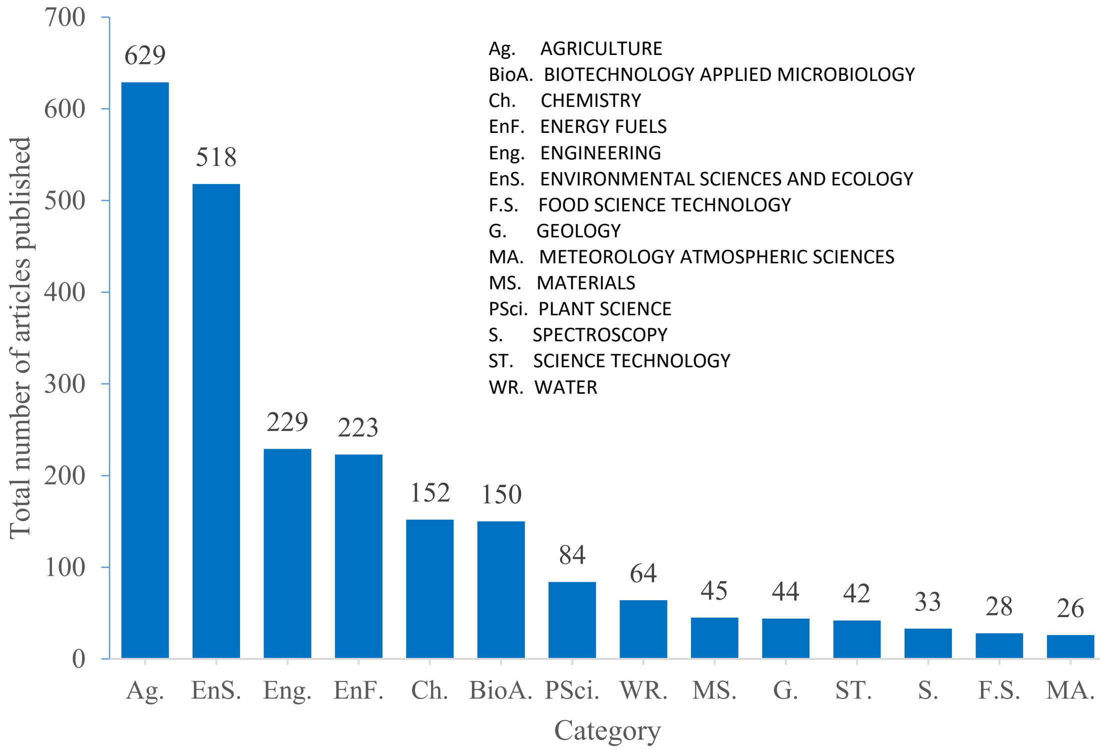

Figure II.2: Number of articles on biochar published between 2005 and 2015, categorized by subject. Note: some articles may fall into two or more categories

The 14 most common biochar-related subjects over the timespan of the study were selected, and the number of articles published within each subject area was plotted (Figure II.2). The highest percentage of articles was in Agriculture (37.1%), followed by Environmental Sciences and Ecology (30.5%). By comparison, Kim et al. (2016) found that the greatest percentage was in the Environmental Sciences and Ecology sector, followed by the Agriculture sector. This difference is likely attributable to the fact that the present BA excludes review articles.

Bioresource Technology was the most productive journal (Table II.2), in agreement with the findings of Kim et al. (2016). These results should encourage research groups to publish in and subscribe to the most cited journals to enhance dissemination of their research results.

Table II.2: Top 10 journals based on number of biochar articles published

Journal title	Articles		Times cited	
	2000–2015	Per year	2005–2015	Per article
Bioresource Technology	109	9.1	2,416	345
Chemosphere	64	5.3	1,579	225
Environmental Science and Technology	61	5.1	2,909	323
Journal of Environmental Quality	60	5.0	1,355	194
Soil Biology and Biochemistry	47	3.9	1,849	264
Plant and Soil	45	3.8	1,745	194
Journal of Analytical and Applied Pyrolysis	45	3.8	416	52
Environmental Science and Pollution Research	35	2.9	185	37
Science of the Total Environment	32	2.7	329	66
Agriculture Ecosystems and Environment	31	2.6	572	95

Distribution based on language of publication

The vast majority of articles were published in English (Table II.3). The most widely accepted language for presenting biochar research data is English.

Table II.3: Distribution of biochar articles published 2000–2016 based on the language of publication

Language	No. articles	Percent of total
English	1,687	99.41
Portuguese	4	0.24
German	3	0.18
Chinese	3	0.18
Total	1,697	100

Distribution based on author's country of origin

Authors of biochar articles predominantly originated in the United States, followed closely by the PR of China (Table II.4). Kim at al. (2016), who included review papers in their BA, found China to be the top country, followed by the United States.

Table II.4: Article distribution based on the lead author's country of origin

Country	No. articles	Percent of total
United States	488	28.8
PR China	470	27.7
Australia	175	10.3
Germany	98	5.77
Spain	86	5.07
Canada	77	4.54
South Korea	76	4.48
England	72	4.24
Italy	66	3.89
Scotland	63	3.71
New Zealand	54	3.18
Brazil	49	2.89
Pakistan	46	2.71
Japan	33	1.94
India	33	1.94
Sweden	33	1.83
Denmark	31	1.83
Malaysia	28	1.65
Norway	27	1.59
Switzerland	26	1.53

Top-cited articles

The biochar-related articles generated a total of 36,303 citations, with a mean of 2,135 citations per year between 2000 and 2015. The number of citations generated by a paper does not necessarily indicate quality, but instead the impact of that particular article on the field (Ma et al. 2012). Among the top 10 most-cited biochar-related articles (Table II.5), none were published between 2000 and 2006. Four most-cited articles were published in 2010, two were published in each of 2008 and 2009, and one was published in each of 2007 and 2011. *Environmental Science and Technology* published four articles from the list. Lead authors Chan from Australia and Zimmerman from the United States each contributed two articles on this list.

Table II.5: Top 10 most cited biochar-related articles published between 2000 and 2015

Title	Year	Lead author, *Journal*	No. citations	No. citations per year
Dynamic molecular structure of plant biomass-derived black carbon (biochar)	2010	Keiluweit, *Environ. Sci. Tech.*	387	55.3
Agronomic values of green waste biochar as a soil amendment	2007	Chan, *Austral. J. Soil Res.*	357	30.6
Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures	2008	Chen, *Environ. Sci. Tech.*	275	30.6
Sustainable biochar to mitigate global climate change	2010	Woolf, *Nature Comm.*	270	38.6
Abiotic and microbial oxidation of laboratory-produced black carbon (biochar)	2010	Zimmerman, *Environ. Sci. Tech.*	249	31.1
Impact of biochar amendment on fertility of a southeastern coastal plain soil	2009	Novak, *Soil Sci.*	249	31.1
Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	2011	Zimmerman, *Soil Biol. Biochem.*	247	41.2
Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	2010	Van, *Plant Soil*	244	30.3
Dairy-manure derived biochar effectively sorbs lead and atrazine	2009	Cao, *Environ. Sci. Tech.*	242	30.3
Using poultry litter biochars as soil amendments	2008	Chan, *Austral. J. Soil Res.*	228	25.3

Distribution of most-cited authors

Several authors published multiple articles on biochar. Gao from the University of Florida has been the most prolific researcher regarding the number of articles published, whereas Lehmann from Cornell University has the highest number of citations (Table II.6). In fact, the University of Florida has two authors on the list of the most prolific authors in the field of biochar research. The USA has seven researchers, followed by PR China with five. These results could be helpful for prospective researchers seeking expert advice from an experienced scholar who has extensive knowledge on biochar.

Table II.6: List of most prolific authors between 2000 and 2015

Author	Affiliation	Country	No. articles	No. citations	No. citations per year
Gao	Dept. Agricultural and Biological Engineering, University of Florida	USA	43	1,660	237.1
Lehmann	Dept. Crop and Soil Sciences, Cornell University	USA	38	2,001	222.3
Zimmerman	Dept. Geological Sciences, University of Florida	USA	29	1,660	237.1
Ok	Biochar Research Centre, Kangwon National University	South Korea	28	413	82.6
Van Zwieten	University of New England	Australia	27	1,413	157
Cao	School of Environmental Science and Engineering, Shanghai Jiao Tong University	PR China	26	1,607	178.6
Joseph	School of Materials Science and Engineering, University of New South Wales	Australia	26	1,607	178.6
Uchimiya	Southern Regional Research Center, United States Dept. of Agricultre, Agricultural Research Service	USA	25	983	140.4
Pan	Institute of Resource Ecosystem and Environment of Agriculture, Nanjing Agricultural University	PR China	25	804	134
Zhang	College of Environmental Sciences and Engineering, Nankai University	PR China	24	558	111.6
Xu	Chinese Academy of Science, Institute of Soil Science, State Key Laboratory of Soil and Sustainable Agriculture	PR China	24	814	135.7
Novak	Coastal Plains Soil Water & Plant Research Center, United States Dept. of Agricultre, Agricultural Research Service	USA	24	1090	136.3
Xing	Stockbridge School of Agriculture, University of Massachusetts	USA	23	442	73.67
Li	Key Laboratory of Plant Nutrition and Agroenvironment for Northwest China, Ministry of Agriculture	PR China	23	714	119
Lima	Southern Regional Research Center, United States Dept. of Agricultre, Agricultural Research Service	USA	21	837	119.6
Singh	School of the Environment & Rural Sciences, University of New England	Australia	20	1019	145.6
Cornelissen	Dept. Environmental Engineering, Norwegian Geotechnical Institute	Norway	20	317	63.4

Most research articles dealt with the physico-chemical analysis of biochar rather than the effects of its use as a soil amendment or in other applications. Accordingly, few works were published on different potential methods to apply biochar to agricultural soils and their effects on crop production. Older articles and articles regarding biochar application to soils and crop production received higher citation counts.

Conclusions

1. Bibliometric analysis of 1,697 biochar-related articles published in more than 100 journals between 2000 and 2015 showed an increasing worldwide trend in the relatively new field of biochar research: the number of published articles rose exponentially between 2008 and 2015, and most cited works were published after 2008. If these trends are any indication, new avenues of biochar research are opening at a rapid pace.
2. Journals that published the most frequently cited articles, such as *Environmental Science and Technology* and *Soil Biology and Biochemistry* could prove a better publication venue in terms of maximizing information dissemination (citation counts).
3. As expected, English is the dominant publication language and should be used if authors want to maximize dissemination of research results. Agriculture dominated the subject field, followed by Environmental Sciences and Ecology.
4. Government research funds should be directed more towards agricultural and environmental implications of biochar, to keep pace with the world trend in biochar research. The second-most cited article, published in 2007, notably addressed not only the effects of biochar on soil physical, mechanical and chemical properties but its effects on crop production.

Connecting Text

Chapter II presented a global bibliometric analysis to investigate the primary literature related to biochar research published over the past 15 years. The analysis provided insight into the number of articles published, journals, subjects, citations, and overall trends in biochar research. **Chapter III** presents a review of current knowledge and additional experimental work required to thoroughly understand the influence of biochar amendments on processes occurring in agricultural soils.

Chapter III

Influence of biochar on agricultural soils, crop production and the environment – A review

Abstract

Given its high pore volume and adsorption capacity, and when applied as an agricultural soil amendment, its ability to enhance the soil's nutrient- and water- holding capacities, biochar has become a focus of research interest. In most applications, crop productivity is significantly increased after agricultural soils are amended with biochar. In addition to increasing soil quality, the biochar amendments sequester carbon within the soil. However, the long-term effects of amending agricultural soils with biochar are difficult to predict, because the mechanisms behind the increase in productivity of biochar amended soils are not yet fully understood. Long-term detrimental effects on soil and the environment can occur if biochar is applied haphazardly. Current knowledge and the additional experimental work required to thoroughly understand the influence of biochar amendment on the behavior of agricultural soils processes are reviewed.

Introduction

"Terra Preta" is a particularly fertile anthropogenic soil discovered around the ruins of a pre-Columbian civilization located in the Amazon basin. By comparison, typical Amazonian jungle soils are nutrient poor because heavy rains wash nutrients from the topsoil to deeper soil strata, where they are inaccessible to plant rooting systems. Terra Preta soils were created 2000 years ago by enrichment of native jungle soils with a carbonaceous material (Glaser and Birk 2012), and are conjectured to have been produced when the indigenous Terra Preta peoples buried biomass in pits, where it smoldered and decomposed for days (Brown 2009). Terra Preta soils have remained highly fertile and crops grow vigorously in them because they host large microbial communities that keep nutrients bioavailable (Kim et al. 2007).

Nowadays, researchers try to mimic "Terra Preta soil" by applying biochar (charcoal produced through pyrolysis or gasification of biomass under anaerobic conditions) to improve degraded agricultural soils. Soil amendment with biochar is considered both a way to build the soil organic fraction and to sequester C. More than 2,500 articles documenting the effect of biochar on agricultural soil processes and crop production have been published between 2009 and the present; very few studies were published before 2009. This growing interest indicates that amending soil with biochar is likely to become commonplace. However, accurately predicting the full effects of amending agricultural soils with biochar remains problematic, particularly since it is virtually impossible to remove the highly inert biochar once it is applied to the soil (Lehmann et al. 2009). Given the irreversibility of biochar application, and its undocumented but potential detrimental effects on crop and human health, its impacts on soil processes should be carefully assessed.

Biochar amendment of soils has also raised interest with respect to climate change mitigation. Biochar becomes a C sink during its production, thus could help reduce the C footprint by sequestering C in soils and reducing greenhouse gas (GHG) concentrations in the atmosphere (Hansen et al. 2015). The objectives of this systematic literature review are to highlight the current state of knowledge concerning how biochar influences amended soil physico-chemical properties and its longer-term effects on soil processes and the environment. Moreover, we identify knowledge gaps and provide a framework for future research objectives.

Biochar Production

Biochar is produced by pyrolysis: the decomposition of biomass material in the absence of oxygen at temperatures ranging between 250 and 700°C (Yuan et al. 2014). The organic starting material or feedstock can originate from a variety of types of biomass, including woodchips, crop residues, and animal waste. Pyrolysis conditions are responsible for biochar characteristics such as chemical composition, surface chemistry, nutrient composition, adsorption capacity, cation exchange capacity (CEC), pH, and physical structure (Cimò et al. 2014). The physical characteristics of biochar such as pore size distribution are also influenced by processing conditions (Ronsse et al. 2013); therefore the efficacy of biochar as a soil amendment depends on pyrolysis conditions and the feedstock biomass used. For example, biochar produced at temperatures exceeding 450°C is most likely to improve soil drainage and make more water available to plants, whereas charcoal produced at lower temperatures can repel water (Page-Dumroese et al. 2015).

Cellulosic compounds remain in biochar created below a temperature range of 300–400°C; higher temperatures results in the structural breakdown of such compounds (Antal and Grønli 2003). Therefore, biochar produced at lower temperatures has a higher soil nutrient retention capacity because it contains more functional groups, which act as nutrient retention sites (Ashworth et al. 2014; Glaser et al. 2002). On the other hand, the porosity of biochar increases with the temperature of pyrolysis due to volatilization of tars from pores at higher pyrolysis temperatures (Cantrell et al. 2007). The influences of pyrolysis temperature and feedstock on biochar pore volume and surface area are presented in Table III.1.

Biochar Post-Production

Biologically activated biochar

For biochar to become biologically active and efficiently exhibit soil-enhancing properties, it needs to be activated, such that surfaces and pores are opened up to interact with the soil. Activation of biochar in soils occurs naturally and can take months to years, thereby providing increasing benefits in soil over time. For example, biochar may increase its ability to adsorb and retain nutrients and water, making them more available to plants (Cross and Sohi 2013).

Table III.1: Effect of feedstock and pyrolysis temperature on biochar pore volume and surface area

Feedstock	Pyrolysis temperature (°C)	Pore volume (m^3/t)	Surface area (m^2/g)	Reference
Malt spent rootlets	400	3.4	0.016	Manariotis et al. 2015
	800	340	0.21	
Hardwood	300	0.06	NA	Xiao and Pignatello 2015
	500	0.21	NA	
Wheat	400	0.016	10.15	Manna and Singh 2015
	600	0.034	20.38	
Biosolids	650	NA	395	Kaudal et al. 2015
Goat manure	400	0.0013	NA	Touray et al. 2014
	800	0.049	NA	
Wood	350	NA	1	Brewer et al. 2014
	800	NA	317	
Rice husk	350	NA	32.7	Claoston et al. 2014
	650	NA	261.72	
Empty fruit bunch	350	NA	11.76	
	650	NA	28.2	
Rubber wood	300	0.0034	1.40	Shaaban et al. 2014
	700	0.0097	5.49	
Medicinal herbs	300	4.45	0.0075	Yuan 2014
	700	11	0.0178	
Coal tailings	400	NA	2.7	Tremain et al. 2014
	800	NA	75.3	
Pine needle	100	NA	0.65	Tang et al. 2013
	700	NA	490.8	
Cotton seed hulls	350	NA	4.7	
	800	NA	322	
Oak wood	350	NA	450	
	600	NA	642	
Corn stover	350	NA	293	
	600	NA	527	
Broiler litter manure	350	NA	59.5	
	700	NA	94.2	
Soybean stalk	300	NA	144.2	
	700	NA	250.2	
Pine needles	300	NA	4.09	Ahmad et al. 2013
	700	NA	390.5	
Sewage sludge	400	NA	33.4	Méndez et al. 2013
	600	NA	37.2	
Switchgrass	450	NA	5.89	Kim et al. 2013
	800	NA	52.3	
Switchgrass	250	NA	0.4	Ippolito et al. 2012
	500	NA	62.2	
Bagasse	400	0.03	14.4	Kameyama et al. 2012
	800	0.16	219	
Maize	300	NA	1	Wang et al. 2015
	600	NA	70	

NA: Data not available

The natural process of activation in soil can be accelerated by mixing biochar with compost or manure (Dias et al. 2010; Jindo et al. 2012). Biochar generated at lower temperatures and not receiving further activation or processing will have lower adsorption capacity and surface area than activated biochar (Plaza et al. 2014). The surface area of non-activated biochar is approximately 10 m^2/kg compared to 200–1,000 m^2/kg for activated biochar (Dehkhoda et al. 2016). Otherwise, biochar can be activated by exposure to steam or chemicals (e.g., sodium hydroxide, potassium hydroxide, carbon dioxide [CO_2] or acids) (Azargohar and Dalai 2008). Another way of activating biochar is by using sewage sludge or zinc chloride to enhance the surface area of the C product (Chen et al. 2002). Compared to digested sludge, undigested sludge produces an activated C of higher C content, lower ash content, greater surface area, and with better phenol adsorption characteristics (Tay et al. 2001).

Activating C to enhance absorption requires specific catalytic chemicals to be loaded onto the C surface. The residual C in both cases is porous, but has a low surface area. To generate a high surface area, chemical treatment is applied after pyrolysis along with a second thermal treatment. This is often followed by a water wash to remove the activating chemical or the unwanted ash (Kirk et al. 2013).

Room temperature treatment of biochar has been shown to effectively and rapidly oxidize its surface, thereby significantly increasing the number of acidic oxygenated (e.g., carboxylic acid) groups on its surface. Carboxylic acid groups are essential in improving biochar nutrient holding capacity (Park et al. 2013). Moreover, polarizing the acidic nature of oxidized biochar means that they may be well suited for the retention of basic ions such as ammonium (NH_4^+) or other cations. A strong correlation exists between the quantity of NH_4^+ adsorbed by the oxidized C and the concentration of acid groups on biochar (Kastner et al. 2012).

Given the extra step required to activate biochar, it would not always be economical to use biochar as a soil amendment (Kuppens et al. 2014). To minimize the cost of the activation process, further research is needed to quantify the effect of the temperature and pyrolysis rate on the pore size distribution and adsorptive capacity of biochar.

Fortifying biochar with nutrients

A toxic gas that is a byproduct of biogas production systems, hydrogen sulfide (H_2S) increases the rate of corrosion in engines utilizing biogas. This corrosion may be prevented by separating and removing H_2S from the biogas (Powell et al. 2012). In the process of adsorption of H_2S on activated biochar, the surface of the activated bio-carbon serves as a site where H_2S is completely converted into elemental sulfur and sulfates. Such a system provides an environmentally sustainable method for disposal of H_2S in agricultural soil, where it can act as a fertilizer and provide sulfur to crops (Patel 2013). Camphor-derived biochars produced at pyrolysis temperatures of 100–500°C have been proven effective in H_2S sorption, with pyrolysis temperature and surface pH being the production parameters with the strongest influence on H_2S adsorption capacity (Shang et al. 2012). A small percentage of oxygen or air must be added to the gas stream to provide the oxidation potential needed to convert H_2S to either sulfur or solid oxidized sulfur compounds (Shang et al. 2016). Given their greater surface area, activated C fibers show greater adsorption and retention capacities for sulfur, and heat treatment further enhances these characteristics (Feng et al. 2005). These observations are helpful for designing biochar as engineered sorbents for the removal of H_2S from biogas production units. Future research in the development of mechanisms to fortify biochar with nutrients is strongly needed.

Biochar pelletizing

Pelletizing biochar might provide a means to engineer biochar for a particular degraded soil condition and reduce dust generation when applied to soils (Andrenelli et al. 2016). Handling and applying biochar to soils could pose health hazards associated with inhaling small airborne particles of biochar. Pellets reduce dust formation and give the product a uniform shape and size, and also allow biochar to be more uniformly distributed in the soil (Reza et al. 2012).

Addition of starch and polylactic acid to achieve pellet integrity could provide more resistance to stresses developed during water sorption and swelling. Attempts to pelletize biochar using binders without wood flour failed to yield a cohesive pellet, but adding canola oil at a dosage of 3% improved the rheology of the blend, allowing for an improved pellet output rate and integrity (Dumroese et al. 2011). Most research in pelletizing biochar focuses on densifying pellets to obtain higher packing efficiencies. However, low density pellets have more desirable swelling coefficients. During pellet formation, using a larger die diameter and reducing die length could reduce pressure and therefore pellet density, and better maintain native biochar porosity (Reza et al. 2012). Such designs could be augmented with nutrients to further enhance pellet performance as a soil amendment. For example, biochar pellets have been produced by blending switchgrass (*Panicum virgatum* L.) biochar, lignin, and potassium and phosphorus fertilizers, followed by pelletization (Kim et al. 2014).

Future study of additives to biochar to increase the coherence and resistance of pellets for better transportation and application to soils is recommended. The best pretreatment conditions in making strong biochar pellets should be assessed by measuring pellet resistance to abrasion and immersion, along with their modulus of elasticity and equilibrium moisture content. Moreover, calculations of pellet modulus of elasticity and compressibility are needed to develop standards.

Similar to manure, minerals, and compost, the efficiency of soil amendments varies according to how they are applied and incorporated (e.g., surface applied, banded, or broadcast). Biochar application techniques, especially with pelletized biochar, should be investigated to achieve the highest possible application efficiency.

Influence of Biochar on Agricultural Soils

Biochar amendment alters the physico-chemical properties of soil, including bulk density (ρ), porosity, CEC, and pH (Atkinson et al. 2010). Such soil amendments influence soil processes such as water- and nutrient-holding capacity and consequently influence crop production.

Soil-biochar mix physical characteristics

Biochar significantly affects the physical nature of agricultural soils. These changes affect plant growth by altering root penetration depth and availability of water. Biochar particles are less dense than soil particles (Sharma et al. 2014); therefore, adding biochar to soil will lower soil ρ. Soils with a lower ρ have lower energy requirements for mechanical tillage (Carter 1990).

In soils vulnerable to compaction, consequences of biochar amendment may be either positive or negative in the topsoil and subsoil. Biochar has a low elasticity, measured in terms of relaxation ratio—the ratio of the test material ρ under the specified stress to ρ after the stress is removed. By comparison, straw has a very high elasticity ratio; therefore, when straw biochar is applied instead of fresh straw, the resilience of the soil to compaction loads changes. On the other hand, an obvious risk of compaction occurs through the very application of biochar, particularly if biochar is applied with heavy machinery while the water-filled pore volume of soil is relatively high (Gracia et al. 2012).

Roots are flexible in terms of elongation and proliferation and are affected by mechanical impedance within the soil profile. High ρ soil has high root growth impedance, which reduces crop productivity (Otto et al. 2011) by decreasing the root elongation rate via a decrease in the cell division rate in the meristem and a decrease in cell length rather than volume (Bengough and Mullins 1990).

Biochar amendment alters soil porosity and increases soil surface area; accordingly, a soil-biochar mix tends to display a higher water-holding capacity (WHC) than unamended soil (Basso et al. 2013). Soil water retention curves (SWRCs) showed an increase in soil WHC with application of biochar (Abel et al. 2013). Nevertheless, this additional water may not be readily available to plants, since water in very small saturated pores is not suitable for uptake (Sohi et al. 2010). As the rate of biochar amendment rises, so does soil volumetric water content, largely due to the alteration of micropores (Zeelie 2012). In another study, biochar produced from vegetable bio-products and applied to soil at a dosage of 60 t/ha showed inconsistent soil water retention (Ventura et al. 2013). This inconsistency was attributed to non-homogeneous soils and biochar hydrophobicity. Applying biochar to sandy soil at a dosage of 60 t/ha significantly increased soil water retention, which was attributed to the porous structure of biochar (Ulyett et al. 2014). In another study, biochar amendment at a rate of 20 g/kg increased water retention in sandy loam (SL) soil, resulting in a 12% reduction in cumulative evaporation (Kameyama et al. 2014). Further, the soil water retention at saturation and at field capacity increased by 30 and 16%, respectively.

Soil amendment with biochar derived from different feedstocks affects soil hydrology differently: soil amended with woodchip biochar had a higher water content than soil amended with dairy manure biochar (Lei and Zhang 2013). Moreover, soil water content increased with increasing biochar dosage (Ibrahim et al. 2013). Both woodchip or dairy manure biochar mixed at 5% (w/w) with soil increased the saturated hydraulic conductivity (k_{sat}) of the amended soils, but the effect was more pronounced for woodchip biochar due its relatively high ash content (Lei and Zhang 2013).

The electrical charge on clay particles causes rearrangement of soil particles. Biochar amendment decreases the k_{sat} of clay soils since clay particles move closer together as their electrical charge changes. The biochar ash fraction causes similar effects (Osinubi and Eberemu 2013). Adding up to 6% (dry wt.) biochar to clayey soil decrease k_{sat} by up to 78% (Liu 2012) whereas adding 4% of *Conocarpus* biochar increased sandy soil k_{sat} by 25% (Ibrahim et al. 2013).

Biochar can introduce hydrophobic compounds to soils, which might inhibit plant growth (Fang et al. 2013). Biochar produced at temperatures below 450°C tend to retain organic compounds that repel water (Kinney et al. 2012; Yi et al. 2015). This hydrophobicity may also lead to soil erosion due to increased overland flow (Conte et al. 2013). The hydrophobicity of biochar can be controlled by appropriate choices of feedstock and pyrolysis conditions. Post-pyrolysis treatment with water can be used to decrease biochar hydrophobicity (Yi et al. 2015).

To conclude, effects of biochar on soil hydrology need to be studied experimentally in both the laboratory and field (e.g., SWRCs and water availability to plants), which will facilitate modeling to identify the soil management strategies best suited to a specific site. The mechanisms underlying how the physical characteristics of biochar influence compaction and water flow and how these properties change over time are not well understood. In order to understand how the physical nature of biochar influences soil processes over time, methods may be developed to: (i) mimic the behavior of soil after years of biochar amendments, such as using artificially aged soil-biochar mix (Song et al. 2013), and (ii) investigate the effect of applying biochars derived from different feedstocks and pyrolysis conditions and at different rates to different soils under various environmental and agricultural conditions. However, at present controlled long term-studies are not available in the literature. Moreover, conservation methods such as no-till, cover crops, complex crop rotations, mixed farming systems, and agroforestry need to be considered in the context of biochar amendments to the soil. The effect of biochar amendment on soils prone to compaction and its influence on soil processes and root systems, as well as its effect on friction and cohesion between soil particles and biochar, remain poorly quantified. Moreover, the phenomenon of swelling-shrinkage dynamics of soil-biochar mixes must be studied because it exerts a strong influence on the improvement of soil compaction.

Very little information is available on how biochar could impact irrigation frequency or intensity on a large scale. Soil hydrology may be affected by partial or total blockage of soil pores by the smallest size fraction of biochar, thereby decreasing water infiltration. Thus, biochar application may be beneficial or detrimental, depending on biochar particle size and on the texture of the soil being amended. Accordingly, further investigation is required on the effect of biochar particle size distribution on hydrological soil properties and plant water uptake to optimize soil texture and biochar properties.

Soil-biochar mix fertility

Since the chemical compositions of biochar and soil differ (Yuan et al. 2016), biochar can potentially alter plant growth through its alteration of soil chemistry and modification of the availability of nutrients to roots. The CEC represents the number of exchangeable cations per dry weight of soil, which the soil is capable of retaining at a given pH value when it is wet. These cations are available to be exchanged with other cations present in plant roots or in the soil water solution. The CEC is a measure of soil fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination (Havlin et al. 2005)**.** The greater the CEC, the greater the soil fertility (Havlin et al 2005). When soil pH decreases (more acidic), more H^+ ions are attached to colloids, thereby displacing cations into the soil water solution. When soil pH increases, fewer cations are available in solution because there are fewer H^+ ions to displace cations into the soil solution from the colloids; in other words, the CEC increases (Havlin et al. 2005). Crop yield is relatively high in soils with a higher percentage of clay, since clay particles have a high CEC. Biochar derived from animal wastes significantly increased soil pH and CEC of acidic free-draining soils (Uzoma et al. 2011; Yuan et al. 2014).

Nitrogen (N) is an essential component of all proteins, nucleic acids, and many other important biomolecules. Accordingly, plant N deficiency most often results in slow stunted growth and chlorosis (Havlin et al. 2005). Since N promotes plant growth, it is common to add N to the soil to maintain or improve plant growth and health. To increase crop production, inorganic N fertilizers containing nitrate (NO_3^-) and NH_4^+, which are easily absorbed by plants, are introduced to the plant root zone (Davis 1997). However, soils do not absorb the excess NO_3^- ions, which can then move freely downward with drainage water, leaching into groundwater, streams, and eventually oceans (Forrestal et al. 2014). The degree of leaching is affected by soil texture and structure. Biochar-mediated improvement in soil texture and structure leads to a decreased leaching of nutrients to groundwater. On the other hand, if pure biochar is incorporated into the soil without activation, its high adsorption capacity will result in the adsorption and fixing of available nutrients in the soil, thereby barring the crop from benefiting from soil nutrients. Thus, crop growth might be inhibited immediately after biochar amendment (Lehmann et al. 2011).

Activated biochar enhances the adsorption of soil nutrients (Kameyama et al. 2012) because biochar-amended soil not only holds more water and nutrients than its unamended counterpart, but also makes nutrients readily available to plants (Rogovska et al. 2014). Organic N exists in materials formed from microbial, animal, and plant activities that generate manure, sewage waste, compost, and decomposing roots or leaves. These organic materials transform into soil material termed humus. However, plants cannot use organic forms of N; therefore, the presence of nitrifying soil microorganisms is necessary to convert organic N into inorganic N that plants can take up and use (Brady and Weil 1996). Microorganisms housed in biochar micropores multiply more rapidly as they are sheltered from larger predators, which are unable to access these micropores. Higher microbial reproductive and retention rates in biochar amended *vs*. unamended soils have been noted (Lehmann et al 2011). Biochar-amended soils contain as much as 35% (dry wt.) soil organic C in the form of charcoal (McHenry 2011).

Soil aggregates are groups of soil particles that bind to one another more strongly than to adjacent particles, creating pore space for the retention and exchange of air and water. Aggregate stability refers to the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied. Wet aggregate stability represents how well a soil can resist raindrop impact and water erosion, while the size distribution of dry aggregates can be used to predict resistance to abrasion and wind erosion. The higher the stability of soil aggregates, the greater is the soil fertility. Soil OM and microbial activity were enhanced due to the high pore structure of biochar and the presence of degradable components in the biochar. These enhancements provide binding agents that improve soil macro-aggregates (Lu et al. 2014).

To conclude, relationships among soil OM, the type of biochar amendment, and crop yield are poorly understood. How biochar amendment affects soil physical properties and chemistry (e.g., oxidation of nutrients due to increased porosity of the soil-biochar mix) should receive more attention to fully quantify the physico-chemical behavior of soil-biochar mixes. The aggregate strength is influenced by the soil structure, yet biochar-mediated modifications to soil structure and consequently to aggregate tensile strength have not been fully elucidated.

Plant Production in Soil-Biochar Mix

Several studies have reported positive effects of biochar amendment on crop productivity (e.g., Asai et al. 2009; Baronti et al. 2014; Blackwell et al. 2010; Galinato et al. 2011; Graber et al. 2010; Hossain et al. 2010; Jeffery et al. 2011; Revell et al. 2012; Uzoma et al. 2011b; Wang et al. 2014). Statistical meta-analyses have shown that biochar amendment increases crop productivity by 13% in acidic and neutral pH soils by increasing soil pH (liming effect) (Hass et al. 2012). Increases in crop production in coarse or medium textured soils were due to improved soil WHC and nutrient availability (Jeffery et al. 2011). Plants exhibit thinner and more extensively branched roots with increased biochar amendment, due to the enhanced WHC and reduction of N and P leaching from the soil (Bruun et al. 2014; Ventura et al. 2013). While biochar soil amendments increase nutrient availability to roots and improve crop yield, few studies have explained the mechanisms behind this process. This lack of information can be attributed to three main causes:

(i) Given the variety of biochar feedstocks, along with the inherent biophysical characteristics and agronomic practices of different study sites, it is difficult to generalize benefits achieved through biochar amendment.

(ii) In experimental field trials, it is often difficult or impossible to control all environmental variables in an experimental design, especially variability in meteorological factors. This can lead to weaknesses in the data obtained from such experiments, and reduce confidence when extrapolating results under other environmental conditions.

(iii) The heterogeneity of biochar poses difficulty in predicting biochar's behavior in agricultural soils. However, this heterogeneity could be utilized in designing a targeted biochar to improve a specific degraded soil.

A paucity of data exists on the effects of biochar on crop production. Therefore, more evidence regarding effects of biochar on soil processes is needed before a large-scale implementation policy can be developed. Such studies could be achieved by developing mechanistic soil process simulations from short-term experiments to predict long-term effects. Despite the fact that biochar can be engineered by altering production conditions and varying feedstock, very little information has been published on the effect of varying biochar particle size or other qualities on soil physico-chemical properties.

Environmental Implications of Biochar Production and Application to Agricultural Soils

Biochar recalcitrance in agricultural soils

Interest in biochar has grown, not only for its benefits as an organic fertilizer, but also as part of an effort to fight global climate change (Woolf et al. 2010). If organic wastes are left to decompose naturally, they release the GHGs CO_2 and methane (CH_4) to the atmosphere (Thomazini et al. 2015). The lack of oxygen and high heat in the pyrolysis process "lock" C in the biochar. Thus, applying biochar to soil can sequester C and decrease GHG concentrations in the atmosphere (Zhang et al. 2016).

Biochar is considered highly recalcitrant because it contains aromatic Cs, which do not decompose easily (Sun 2012). The reported residence time for wood biochar (WBC) is 1,000–12,000 years (Lehmann et al. 2009). Pyrolysis temperature strongly influences the recalcitrance of biochar. Lower-temperature biochar is less stable and could return significant amounts of C to the atmosphere within a few years (Kinneya et al. 2012). Therefore, more research is needed to determine an optimum pyrolysis temperature to produce biochar with high aromatic C content and recalcitrance.

Biochar relocates from the surface to the subsoil through tillage and due to soil shrinkage-swelling cycles (Eckmeier et al. 2007). Laboratory-based studies using freshly made biochar tend to show mass loss—sometimes quite large—over a period of days to years. The long-term stability against measurable short-term decomposition suggests that biochar comprises both stable and degradable components (Kimetu and Lehmann 2010). Combustion conditions during pyrolysis, as well as the type of feedstock, are probably influential in determining the proportion of relatively labile components in biochar products (Singh et al. 2012). Measuring the influence of biochar production parameters is essential for the optimization of pyrolysis for maximum net C sequestration (Alvarez et al. 2014). The chemical composition of biochar confers its high level of stability and is reflected in its elemental composition: highly aromatic and with a very high C content (Quilliam et al. 2013). It is likely that biochar stability is associated with its physical properties and structure. If the biotic and abiotic processes determining the fate of biochar are the same as those for other soil OM, higher soil temperature, moisture availability, lower clay content, and intensive tillage will accelerate its decomposition rate (Mašek et al. 2013).

Soil respiration is essential in assessing the quantity of C losses to the atmosphere from soil (Sohi et al. 2009). Soil C is difficult and expensive to measure due to its spatial variability and complexity; therefore, computer modeling is a practical way to study the effect of various agronomic treatments on soil C. If the dynamics of biochar are quantified, the rate and mode of application can be optimized. Furthermore, knowing what soil type best retains C is valuable.

When biochar is applied as very fine particles, or when larger biochar particles disintegrate in arable soils under the influence of tillage and cultivation operations (Wang et al. 2013), these particles can fill up small pores in the soil, leading to higher ρ and the formation of a subsurface hard pan (Verheijen et al. 2010). Biochar particle size is likely to be reduced by mechanical disturbance such as ploughing or by freeze thaw cycles (Sohi et al. 2009). Little has been published about how agricultural practices could affect biochar particle degradation.

To conclude, biochar loss and mobility through the soil profile and its transport mechanisms require further investigation. More research is required to establish rates of breakdown. Presently insufficient data exist in the literature to compare responses between short- and long-term stability of biochar under different climate regimes and in different soils. Therefore, possible effects of biochar amendment on the environment remain unclear. Assessing the potential impact of amending agricultural soils with biochar on environmental risk and/or sustainability of agricultural soils with simulation models has received very little attention in the literature, though this approach holds great promise.

Sequestration of GHGs in soil

Biochar application to soil reduces CO_2 and nitrous oxide (N_2O) efflux from soils to the atmosphere, which could mitigate climate change (Woolf et al. 2010). Moreover, soil aeration increases following biochar amendment to soil, and contributes to suppression of soil N_2O release (Suddick and Six 2013) at relatively high moisture contents by increasing the soil WHC (Van Zwieten et al. 2009). Case et al. (2012) showed N_2O emissions were suppressed when soil was amended with hardwood biochar at a dosage of 22 t/ha. By comparison, biochar amendment of sandy loam soils did little to enhance soil aeration and the concomitant suppression of soil N_2O emissions (Singh et al. 2010). The microbial or physical immobilization of NO_{3-} in soil following biochar addition may significantly contribute to suppressing soil N_2O emissions (Taghizadeh-Toosi et al. 2011). However, when biochar is applied to soil, it initially leads to the decomposition of soil OM and hence increases CO_2 release to the atmosphere (Augustenborg et al. 2012).

Different forms of inorganic N are bioavailable to plants, some of which can be stored in the soil (e.g., NH_4^+) and some that are not held by soil particles (e.g. NO_3^- and NO_2^-). Inorganic N can either leach through the soil and into the groundwater, or be transformed into nitrogenous gases (N_2, NO, N_2O, NH_3), which diffuse into Earth's atmosphere (Augustenborg et al. 2012). The influence of biochar addition to soils on the mechanism of binding N gases is poorly understood and the net suppression and release of GHGs from soil has not fully been quantified in the literature.

Overall, there is a lack of long-term studies on the effects of biochar application on soil-plant relations and C sequestration. However, engineered biochar should help manage C in soil for long-term sustainability. However, biochar production is associated with emissions of toxic compounds such as polycyclic aromatic hydrocarbons, dioxins and particulates, which can adversely affect human health and pollute the environment (Kuppens et al. 2014). Assessment of this health concern is lacking in the literature.

Conclusions

It could be concluded that it is difficult to generalize benefits biochar due to the several reasons: -

1. Environmental conditions.
2. Heterogeneity of biochar.
3. Compactability of Soil-biochar mix is still not understood.

Connecting Text

In **Chapter III**, a thorough literature review was conducted to highlight biochar production, post-production, and techniques to fortify biochar. The current understanding of the behavior of soil-biochar mixes was presented. The lack of knowledge regarding the effect of applying biochar to agricultural soils was also discussed. Based on the findings from Chapter III, laboratory screening investigations were carried out to study the influences of wood-derived biochar (WBC) on various soil physico-mechanical properties. The WBC varied in particle size and dosage, and one soil texture was used, namely a silty loam.

Chapter IV describes the common materials and methods utilized in the subsequent chapters V, VI, VII, and VIII.

Chapter IV
Materials and Methods

Materials

Soils

In **Chapter V**, the silt loam (STL) soil used was collected from the A horizon (0–20 cm) of a field (UTC 45° 24' 50.1" N, 73° 56' 29.29" W) on the Macdonald Campus Farm, McGill University (Sainte-Anne-de-Bellevue, QC).

In **Chapters VI, VII, and VIII**, sandy loam (SL) and clay loam (CL) soils were used, which were collected from the A horizon (0–20 cm) of two fields (UTC 45° 25' 35.8" N, 73° 56' 21.1" W and 45° 25' 35.5" N, 73° 55' 37.0" W, respectively, on the Macdonald Campus Farm, McGill University (Sainte-Anne-de-Bellevue, QC). The soils were air-dried at room temperature and then sieved to pass through a 2-mm sieve.

Wood-Derived biochar (WBC)

In **Chapters V, VI, VII, and VIII** the WBC used was produced by thermal decomposition (500°C) of forest wastes—including maple (*Acer* sp.) wood. It was purchased from a local market (Maple Leaf® Charcoal, Charbon de Bois Feuille d'Érable Inc., Sainte-Christine d'Auvergne, QC).

Methods

WBC particle size

Chapters V, VI, VII, and VIII

Soil particle size was quantified according to ASTM D7928 (ASTM International 2017). The WBC was ground in a blender then sieved in a fumehood into four particles size ranges: 0.5–210 µm (PS_1), 210–420 µm (PS_2), 0.5–420 µm ($PS_{1,2}$), or 420–841 µm (PS_3). The smallest particle size was determined through laser diffraction analysis using a SympaTEC-HELOS/BF laser diffraction sensor (Clausthal-Zellerfeld, Germany) after and Müller et al. (2004) and Rees et al. (2014).

Mixing of soil and WBC

Chapters V, VI, VII, and VIII

To achieve the desired WBC dosage, dry soil and WBC were homogenized for 20 min. in a soil mixer (Tables IV.1 and IV.2). The SL soil amended with 10% PS_3 WBC and compacted with 25 rammers blow is indicated as SL-PS_3-10%-25B. A 10% dry wt. amendment corresponds to field applications of 375 t/ha, assuming a soil ρ in the field of 1.25 t/m^3 and an application depth of 30 cm.

Bulk density and maximum bulk density

In **Chapters V, VI, VII, and VIII** the loose dry density (ρ_o) determinations were performed by dividing the oven-dry mass of the soil, WBC, or WBC-soil mixture by its volume. The ρ_{max} and θ_{opt} were determined through the standard Proctor compaction test (ASTM D698-07; ASTM International 2007). The standard compaction mold has 101.5 mm diameter and 116.4 mm depth (volume 942 cm^3). The rammer diameter is 50.8 mm, weight is 2.5 kg and falls a distance of 305 mm.

The relative increase in density (RID (%)) was calculated as (ρ_{max} - ρ_o /ρ_o)*100

Soil consistency limits

Chapters V, VI, VII, and VIII

Soil consistency limits in terms of θ_{pl} and θ_{ll} were determined as the Atterberg limits following ASTM D4318-10 (ASTM International 2010). Soil θ_{pl} are the soil moisture contents at which the soil changes from a semisolid state to a plastic state; whereas the θ_{ll} are the soil moisture contents at which the soil changes from a plastic state to a liquid state. The *PI* is the difference between the θ_{pl} and θ_{ll}.

Penetration resistance and shear strength

The penetration resistance (PR) of the compacted soils in the standard Proctor mold was determined by a penetrometer (FieldScout, SC900 Soil Compaction Meter) according to ASAE S313.3 (ASAE international 1991). The penetrometer cone diameter is 12.7 mm and the cone angle is 30°. The Torvane with vane size 19 mm (Humboldt, H4221 Geovane) was used to determine the soil shear strength (τ) of the compacted soil in the standard Proctor mold. Penetrometer and shear vane readings at four depths ranges (2.5, 5.0, 7.5, and 10 cm) were averaged following the procedures described by Ohu (1985).

In **Chapter V**, the STL soil PR and τ were determined at the soil ρ_{max} and θ_{opt} (i.e., at the peak of the compaction curves) after 25B.

In **Chapters VIII** the PR and τ of compacted SL and CL soils were determined at eight moisture contents; for the SL (3–15%) and CL (8–23%) after 5B, 10B or 15B. The minimum of 5B was chosen because it is the minimum number of blows applicable to produce a homogeneous compacted soil in the standard Proctor mold and is within the range of compaction of heavy farm machinery.

Experimental design and statistical analysis

In **Chapter V**, the STL and PS_1, PS_2, or PS_3 WBC particles sizes were factorially combined with 2, 5, and 10% WBC dosages (3×3 factorial design) in triplicate (Table IV.1).

In **Chapters VI, VII, and VIII**, SL and CL soils and two WBC particles size ranges ($PS_{1,2}$ and PS_3) were factorially combined with five WBC dosages (0.5, 1.75, 3, 6, and 10%). Thus, for each soil type, the design included two particle size ranges × 5 WBC dosages (Table IV.1).

In **Chapters V, VI, VII, and VIII**, the analysis of variance (ANOVA) and the Least Significant Difference were used to test mean differences in the responses using SPSS software program (v.

23, IBM SPSS Statistics for Windows, Armonk, NY: IBM Corp). Means and standard deviations of means for triplicate samples are presented. An alpha of 0.05 was chosen.

The experimental design for Chapter V is illustrated in Table IV.1; whereas the experimental designs for Chapters VI, VII and VIII are illustrated in Table IV.2.

Table IV.1: Design of experiments to test effects of wood-derived biochar (WBC) amendments on the characteristics of triplicate silt loam soil samples

Soil type	**WBC dosage (% dry wt.)**	**WBC particle size range**		
		0.5–210 μm (PS_1)	210–420 μm (PS_2)	420–841 μm (PS_3)
Silt loam	**2**	**3***	**3**	**3**
	5	**3**	**3**	**3**
	10	**3**	**3**	**3**

*Number of replicates

Table IV.2: Design of experiments to test effects of wood-derived biochar (WBC) amendments on the characteristics of triplicate sandy loam and clay loam soil samples

Soil type	**WBC dosage (% dry wt.)**	**WBC particle size range**	
		0.5–420 μm ($PS_{1,2}$)	420–841 μm (PS_3)
Sandy loam	**0.5**	**3***	**3**
	1.75	**3**	**3**
	3	**3**	**3**
	6	**3**	**3**
	10	**3**	**3**
Clay loam	**0.5**	**3**	**3**
	1.75	**3**	**3**
	3	**3**	**3**
	6	**3**	**3**
	10	**3**	**3**

*Number of replicates

Chapter V

Influence of wood-derived biochar on the compactibility and strength of silty loam soil

Abstract

Biochar has been shown to enhance soil fertility and increase crop productivity. However, the influence of biochar on soil compaction remains unclear. Thus, selected physico-mechanical properties of a silty loam (STL) soil amended with wood-derived biochar (WBC) were assessed. For unamended soil, the loose bulk density and maximum bulk density (Proctor test) were 1.05 and 1.63 t/m^3, and the optimum moisture content (Proctor), plastic limit, liquid limit, and plasticity index were 16.5, 17.1, 29.3, and 12.2%, respectively. The penetration resistance and shear strength of the unamended soil compacted in the standard compaction Proctor mold and at its optimum moisture content were 1,827 and 858 kPa, respectively. 10% amendment with WBC in the particle size range of 0.5–210 µm led to relative decreases of 18.1, 14.7, 66.6, and 74.2% in loose bulk density, maximum bulk density, penetration resistance, and shear strength, respectively; a 27.3% relative increase in optimum moisture content; and absolute increases in plastic limit, liquid limit, and plasticity index of 5.3, 13.5, and 8.4%, respectively. The STL soil was less susceptible to compaction when amended with relatively smaller particle sizes range of WBC because soil mechanical impedance was enhanced. On the other hand, the range of moisture over which the soil is susceptible to compaction by external forces increases by decreasing the particle sizes of the WBC.

Introduction

Biochar is produced by pyrolysis, a process whereby biomass material is decomposed in the absence of oxygen at 250–700°C (Yuan et al. 2014). The organic starting material can derive from a variety of biomass types, including wood chips, crop residues, and animal waste. Pyrolysis conditions and feedstock material are responsible for biochar characteristics such as chemical composition, surface chemistry, nutrient composition, adsorption capacity, cation exchange capacity (CEC), pH, and physical structure (Cimò et al. 2014).

Soil compaction is defined as a densification of soil whereby air-filled porosity is reduced, causing deterioration in soil processes. Subsoil compaction is a cumulative process leading to soil packing just below the topsoil (Harris 1971). As compaction increases the soil mechanical impedance, it adversely affects the elongation and proliferation of plant roots (Boone and Veen 1994). These changes can alter moisture and nutrient availability to crops, thereby either increasing or decreasing soil productivity. Carter (1990) found crop yield to be inversely correlated to the soil relative bulk density (RBD); which is the ratio between the soil bulk density (ρ) and the maximum soil bulk density (ρ_{max}) (RBD = $\frac{\rho}{\rho_{max}}$). Similarly, Zhao et al. (2010) showed that maximum tree height at a plantation was achieved when RBD was 0.60–0.68, but those trees were somewhat stunted when RBD was 0.78–0.87.

Changes in soil physical properties lead to changes in soil state under compaction (Chen and Weil 2011). Soil particle density is 2.6 t/m^3 regardless of particle size, whereas the density of wood-derived biochar (WBC) particles with a particle size of < 70 μm ranges from 0.6 to 1.6 t/m^3, depending on the wood source (Hu et al. 2016; Yargicoglu et al. 2015). The relatively low true density of biochar means adding it to soils can decrease soil ρ (Abel et al. 2013; Andrenelli et al. 2016; Atkinson et al. 2010; Jeffery et al. 2011; Laird et al. 2010). For example, Reddy et al. (2015) found the specific gravity (G_s) of silty clay loam (CL) amended with 5, 10, and 20% gasified wood pellets (particle sizes < 420 μm; G_s = 0.81) to decrease from 2.6 to 2.1, 2.0, and 1.8, respectively. Soil optimum moisture content (θ_{opt}) for compaction is the moisture content at which soil reach its ρ_{max} for a given applied specific load. A commonly used method to determine the soil θ_{opt} at ρ_{max}

is the Proctor test (ASTM International 2007). First, soil samples are prepared in the laboratory with a range of θ. Soil samples for each θ are added in layers into a cylindrical mold. Between additions, the soil is compacted with a rammer of a known weight dropped from a known height. The dry densities determined for each θ (Y axis) are plotted against the moisture contents (X axis) to produce a compaction curve for that soil. The ρ_{max} and θ_{opt} correspond to the peak of the compaction curve.

The plastic limit (θ_{pl}) is the water content (%) at which a soil can no longer be deformed by rolling into 3.2 mm thread. The θ at which soil passes from a liquid to a plastic state is called the liquid limit (θ_{ll}) (Das 2002). For soils with more than 10% clay content, the plasticity index ($PI = \theta_{ll} - \theta_{pl}$) increases as the soil clay content increases. However, soils with less than 10% clay content can be plastic if OM is present (Keller and Dexter 2012). These consistency limits can provide a means of describing the degree and kind of cohesion and adhesion between the soil particles and any biochar amendments with respect to the resistance of the soil to deform or rupture. WBC (particle size < 2 mm) amended to CL soil at a dosage of 6% increased the θ_{ll} of the soil from 36.9 to 45% and did not change the soil θ_{pl}, resulting in an increase in the PI from 11.1 to 22.2% (Zong et al. 2016).

Dexter and Bird (2000) defined the optimum moisture for tillage (θ_{till}) as "the water content at which tillage produced the greatest proportion of small aggregates". Soil θ_{till} is related to soil consistency limits and/or Proctor compaction test data (Muller et al. 2003; Wagner et al. 1992). There is a positive correlation between θ_{opt} and the θ_{pl} and θ_{ll} (Barzegar et al. 2004; Dexter and Bird 2000; Mosaddeghi et al. 2009; Mueller et al. 2003). The θ_{pl}, θ_{ll}, and PI can be estimated from the θ_{opt}, as well as the soil clay, silt, and OM content (Wagner et al. 1992). The θ_{till} is $0.9 \times \theta_{pl}$ for soils (Dexter and Bird 2000). Mueller et al. (2003) estimated the θ_{opt} for tillage (θ_{till}) from the θ_{pl}

and θ_{opt} and ρ_{max}; whereas Oren (2014) stated that the ρ_{max} could be estimated from the θ_{ll} and clay content. However, no model exists to estimate consistency limits from the particle size and amount of WBC in soils. Soil structure damage is prevented when tillage occurs at the soil θ_{till} for tillage (Mueller et al. 2003). The soil consistency limits are crucial, not only to estimate compressibility and the optimum workable water content range for tillage operations (Zong et al. 2016), but also in agriculture-related soil irrigation management (Smedema 1993). The consistency limits and the Proctor compaction test parameters are ergonomically relevant in terms of compaction hazard for soils and tillage.

In summary, an increase in soil θ_{ll} and θ_{pl}, over the θ_{opt} value not only results in less compactable and more easily tilled soils, but also a wider workable soil moisture range and greater resistance to mechanical forces. Therefore, the first objective of this study was to determine the effects of WBC application on the consistency limits and the Proctor compaction test parameters of a STL soil.

The incorporation of OM into compacted soils decreases soil ρ and penetration resistance (PR) and increases root proliferation (Dexter 2004; Ohu 1985). Soil PR values exceeding 2,000 kPa are associated with restricted root growth (Singh and Malhi 2006). Busscher et al. (2010, 2011) showed the application of 44 t/ha of pecan shell-derived biochar (2% dry wt.) decreased the PR (measured at θ =10%) of a fine loamy sand from 2.9 to 1.18 MPa and raised the soil ρ from 1.45 to 1.52 t/m^3. Bekele et al. (2015) also showed the PR of a loamy soil was lowered by WBC amendment. Whereas Eastman (2011) found a 25 t/ha WBC amendment did not significantly affect a STL soil PR one year after incorporation, Mukherjee et al. (2014) found the PR of a STL soil amended with WBC to unexpectedly increase after 2 years, and attributed this increase to the influence of post-amendment farm operations on soil physical properties. The shear strength (τ)

of a silty clay soil increased with increasing content from 5 to 10% dry wt., and with decreasing wood pellet derived biochar (this biochar had higher cohesion than the silty loam soil it was amended to) particle size from 4.76 to 0.42 mm (Reddy et al. 2015). Since the influence of WBC amendments on the strength of compacted soils remains unclear, the second objective of this study was to determine the PR and τ of a compacted STL amended with WBC.

Materials and Methods

The materials used and the methods utilized are detailed in Chapter IV.

Results and Discussion

Particle size

Sieve analysis showed that the STL soil is classified as well-graded. The hydrometer analysis showed that the soil contained 17% clay, 77% silt, and 6% sand.

Bulk density, maximum bulk density, and optimum moisture content

The ρ_o of the STL and PS_1, PS_2, and PS_3 WBC were 1.05±0.03, 0.29±0.02, 0.31±0.01, and 0.33±0.02 t/m^3, respectively. The mean ρ_o of PS_1, PS_2, and PS_3 did not differ. Amending the STL soil with 5–10% fine WBC particles (PS_1) decreased soil ρ_o by 13.3–18.1% (p = 0.022–0.010), respectively (Table V.1). As WBC particle size increased, a higher dosage was required to achieve a given decrease in soil ρ_o (10% for PS_2 and PS_3). The ρ_o did not differ between STL soils amended with the three particle sizes at a dosage of 10% ($p > 0.29$) (Table V.1).

Table V.1: Mean ± standard deviation loose dry bulk density (ρ_o) and percent change in ρ_o ($\Delta\rho$) of silt loam soil after wood-derived biochar (WBC) amendment at three dosages and particle sizes

WBC dosage (% dry wt.)	**WBC particle size range**					
	0.5–210 µm (PS_1)		210–420 µm (PS_2)		420–841 µm (PS_3)	
	ρ_o (t/m^3)	$\Delta\rho$ (%)	ρ_o (t/m^3)	$\Delta\rho$ (%)	ρ_o (t/m^3)	$\Delta\rho$ (%)
2	0.97±0.04a(a)	–6.7	1.02±0.03a(a)	–2.9	1.03±0.04a(a)	–1.9
5	***0.91±0.03***a(ab)	–13.3	1.00±0.01b(b)	–4.8	1.01±0.05b(b)	–3.8
10	***0.86±0.05***a(b)	–18.1	***0.90±0.08***a(c)	–14.3	***0.92±0.06***a(c)	–12.4

Values in bold italics differ ($p \leq 0.05$) from unamended soil (1.05±0.03 t/m^3) numbers followed by the same letter without parentheses implies no difference in the same row; whereas same letters with parentheses implies no differences in the same column

Compaction curves for the finest particle size (Figure V.1) and highest WBC dosage (Figure V.2) indicate the ρ_{max} and corresponding θ_{opt} of the STL soil were 1.63±0.03 t/m^3 and 16.5±0.4%, respectively. Amendment of 10% PS_1, PS_2, and PS_3 lowered the ρ_{max} of the STL soil by 14.7% (p = 0.009), 16.4% (p = 0.006), and 15.9% (p = 0.008), respectively (Table V.2). WBC increased the θ_{opt} of the soil by 14–27.3% for 5–10% PS_1 (p = 0.012–0.010), 21.2–34.5% for 5–10% PS_2 (p = 0.003–0.004), and 17.6–32.7% for 5–10% PS_3 (p = 0.007–0.0004). In general, the ρ_{max} and θ_{opt} were not different at the same amendment rate with different WBC particle sizes (Table V.2 and Figure V.2). Reddy et al. (2015) stated that silty CL soil compressibility decreases with an increase in the WBC amendment and with a decrease in WBC particle size. However, they used particles passing sieve 10, 20 or 40, but this study used particles retained between sieve 20–40 or 40–70 or passing sieve 70.

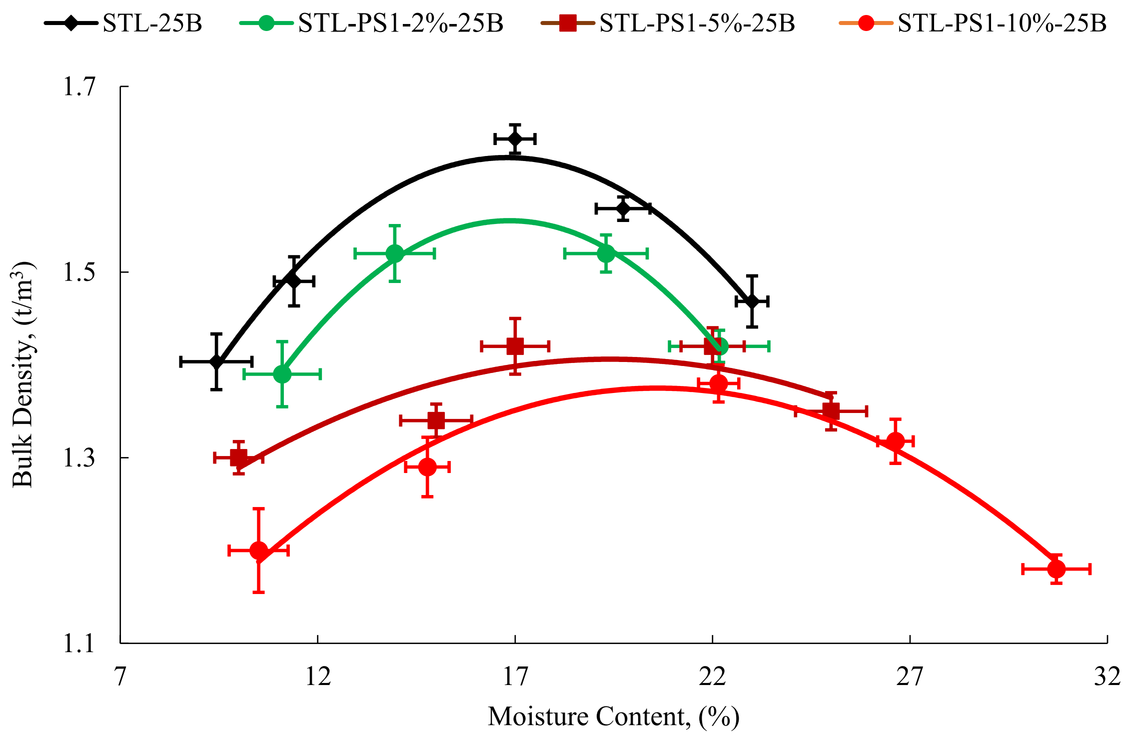

Figure V.1: Compaction curves, 25 blows (25B) of silt loam (STL) soil before and after amendment with 2, 5, and 10% wood-derived biochar with a particle size range of 0.5–210 µm (PS_1)

The unamended soil relative increase in density (RID) was 55.5±4.4; Table V.3 indicates that no dosages changed the RID. At same amendment rate, even though the RID was higher in the PS_1 compared to the PS_2 and PS_3 (Table V.3), there was no changes in the ρ_o and ρ_{max} with different particle sizes (Table V.2).

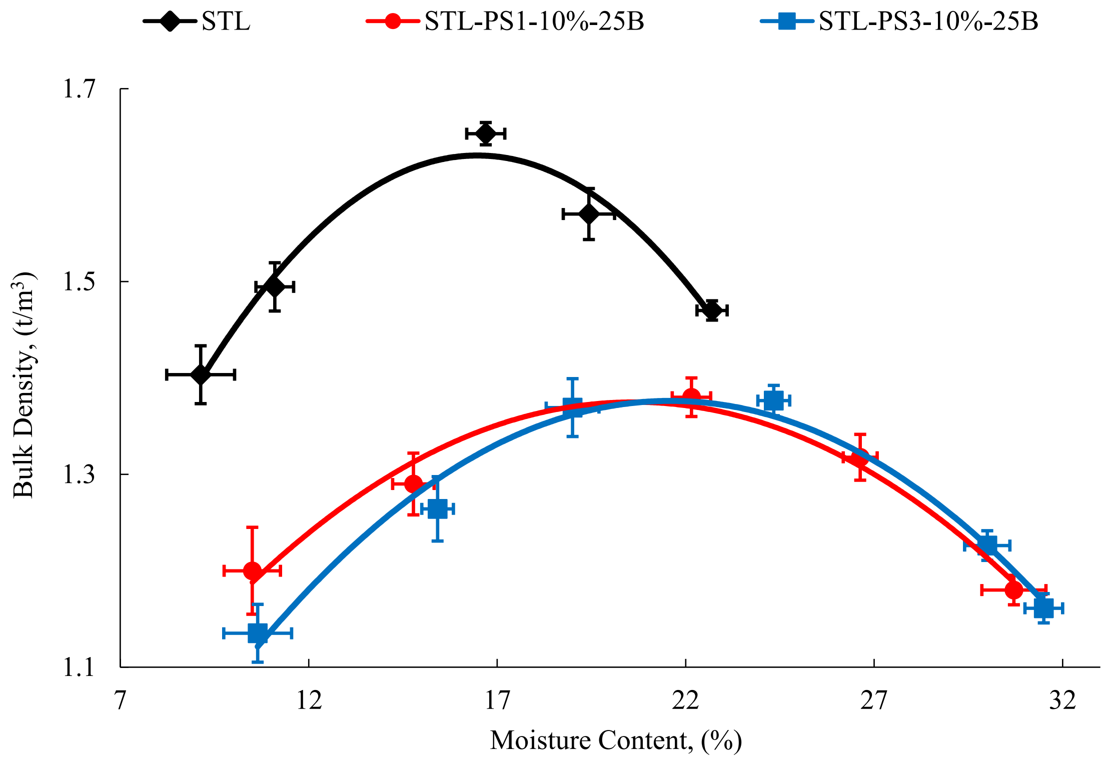

Figure V.2: Compaction curves, 25 blows (25B) for silt loam (STL) soil before and after amendment with 10% wood-derived biochar of two particle size ranges: 0.5–210 µm (PS_1) or 420–841 µm (PS_3)

Table V.2: Mean ± standard deviation maximum bulk density (ρ_{max}), and optimum moisture content (θ_{opt}) of silt loam soil after wood-derived biochar (WBC) amendment at three dosages and particle sizes. $\Delta\rho_{max}$ and $\Delta\theta_{opt}$ is the % difference from the non-amended

WBC (%)	WBC particle size range											
	0.5–210 µm (PS_1)				210–420 µm (PS_2)				420–841 µm (PS_3)			
	ρ_{max} (t/m^3)	$\Delta\rho_{max}$ (%)	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)	ρ_{max} (t/m^3)	$\Delta\rho_{max}$ (%)	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)	ρ_{max} (t/m^3)	$\Delta\rho_{max}$ (%)	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)
2	1.61±0.05a(a)	-1.2	16.8±2.0a(a)	+1.8	1.6±0.09a(a)	–1.8	17.6±1.4a(a)	+6.7	1.59±0.08a(a)	+2.4	17.6±1.3a(a)	+6.7
5	***1.45***±0.06a(b)	–11	***18.6***±2.3a(b)	+14	***1.5***±0.06a(b)	–12.8	***20***±2.7a(b)	+21.2	***1.48***±0.07a(b)	–9.2	***19.4***±1.5a(b)	+17.6
10	***1.39***±0.05a(b)	–14.7	***21***±1.4a(c)	+27.3	***1.36***±0.04a(b)	–16.4	***22.2***±1.3a(c)	+34.5	***1.37***±0.04a(c)	–15.9	***21.9***±1.4a(c)	+32.7

ρ_{max} and θ_{opt} values in bold italics differ ($p \leq 0.05$) from non-amended soil (1.63±0.03t/m^3 and 16.5±0.4%, respectively). No Interaction ($p=0.8$) or difference between the column ($p=0.9$). Numbers followed by the same letter without parentheses implies no difference in the same row; whereas numbers followed by same letters with parentheses implies differences in the same column.

Table V.3: Mean ± standard deviation relative increase in bulk densities (RIB (%)) of silty loam soil after wood-derived biochar (WBC) amendment at three dosages and particle sizes

WBC dosage (% dry wt.)	WBC particle size range		
	0.5–210 µm (PS_1)	210–420 µm (PS_2)	420–841 µm (PS_3)
2	65.1±2.9a(a)	57.5±8.9b(a)	53.0±6.7b(a)
5	60.3±1.3a(a)	49.9 ±4.9b(b)	49.4±6.7b(a)
10	62.8±5.2a(a)	51.2±8.4b(b)	48.5±6.6b(a)

Unamended soil RID (56%±5.1) numbers followed by the same letter without parentheses implies no difference in the same row; whereas numbers followed by same letters with parentheses implies differences in the same column.

Table V.4: Mean ± standard deviation plastic limit (θ_{pl}), liquid limit (θ_{ll}), plasticity index (PI) and change in plasticity index (ΔPI) of silt loam soil after wood-derived biochar (WBC) amendment at three dosages and particle sizes

WBC (%)	**WBC particle size range**											
	0.5–210 μm (PS_1)				210–420 μm (PS_2)				420–841 μm (PS_3)			
	θ_{pl} (%)	θ_{ll} (%)	*PI* (%)	Δ*PI* *	θ_{pl} (%)	θ_{ll} (%)	*PI* (%)	Δ*PI* *	θ_{pl} (%)	θ_{ll} (%)	*PI* (%)	Δ*PI* *
2	18.0±0.9a(a)	30.3±1.5a(a)	12.3±2.1a(a)	+0.1	17.0±2a(a)	29.7±1.6a(a)	12.7±0.6a(a)	+0.5	18.0±2.0a(a)	30.1±1.6a(a)	12.1±0.6a(a)	-0.1
5	***20.3***±1.0a(b)	***39.3***±0.7a(b)	***19.0***±0.8a(b)	***+6.8***	***19.7***±0.9a(b)	***36.0***±3b(b)	16.3±3.6b(b)	+4.1	***20.0***±1.0a(b)	32.0±2.2c(a)	12.0±2.6c(a)	-0.2
10	***22.4***±2.3a(c)	***43.0***±2.9a(c)	***20.6***±1.7a(b)	***+8.5***	***22.3***±2.3a(c)	***37.3***±2b(b)	15.0±0.5b(b)	+2.8	**23.9**±1.8a(c)	***35.0***±2c(b)	11.1±3.2c(a)	-1.0

θ_{pl}, θ_{ll} and *PI* values in bold italics differ ($p \leq 0.05$) from unamended soil (17.1±1.7, 29.3±2.5, and 12.2±4.1%, respectively). Numbers followed by the same letter without parentheses implies no difference in the same row; whereas numbers followed by same letters with parentheses implies differences in the same column.

* absolute difference from non-amended soil

Soil consistency limits

The θ_{pl} of the PS_1, PS_2, and PS_3 amended STL soil was higher than the non-amended STL soil at a 5–10% dosage. No differences in the θ_{pl} were found between the PS_1, PS_2 and PS_3 amended STL at the same amendment rate (Table V.4).

Increasing water content of θ_{pl} over θ_{opt} may imply that soil is more easily tilled at higher θ conditions without structural damage. The non-amended STL soil mean θ_{opt}/θ_{pl} was 0.96±0.09. This ratio did not change for the PS_1, PS_2 and PS_3 amended STL soil. This analysis clearly indicates that the addition of WBC will not extend the range of soil workability without causing compaction, regardless of WBC particle size.

The θ_{ll} values of the 5–10% PS_1, 5–10%-PS_2 and 10%-PS_3 amended STL soil were higher than the non-amended soil (Table V.4). Unlike the θ_{pl}, the θ_{ll} of the STL-10%-PS_1 was higher than the STL-10%-PS_2 and the STL-10%-PS_3, and the STL-10%-PS_2 was higher than the STL-10%-PS_3 amended STL. This could be attributed to differences in the soil pore structure created by incorporation of different WBC particles sizes in the soil.

Amending the STL soil with 5 and 10% WBC at the finest particle size (PS_1) increased the *PI* from 12.2±4.1% to 19±0.8% and 20.6±1.7%, respectively (Table V.4). The PS_2 and PS_3 treatments did not alter the *PI*, which can be attributed to the small increase in θ_{ll} in PS_2 and PS_3 amendments relative to PS_1. The *PI* is an indication of the range of moisture by which soil is susceptible to compaction by applied loads. Since soils with larger *PI* are more prone to structural damage (Aksakal et al. 2013), PS_2 and PS_3 could extend the range of soil workability compared to the PS_1, without causing compaction. Thus, unlike PS_2 and PS_3, the PS_1 WBC applied at dosages of 5 and 10% increased the range of moisture within which soils are most susceptible to compaction and in turn, may decrease the soil workability under tillage operations by extending the range of moisture structural damage to the soil could occur.

The nonamended (*PI* = 12.2±4.1%), PS_1-amended (*PI* = 12.3±2.1–20.6±1.7%), PS_2-amended (*PI* = 12.7±0.6 –16.3±3.6%), and PS_3-amended (*PI* = 11.1±3.2–12.1±0.6%) soils would be classified as medium plasticity (*PI* = 7–17%) according to Mapfumo and Chanasyk (1998a). Thus, amendment with the finest particle size WBC at 5 and 10% dosages changed the soil classification to high plasticity (*PI* > 17). Unlike clay soils—which exhibit high plasticity and are therefore highly prone to compaction—the STL in this study exhibited medium plasticity and was less prone to severe compaction, given the narrow moisture range within which deformation could occur. There is an interaction effect in the PI ($p<0.01$): because the particles are bigger there was no differences in the PI of the PS_3.

In summary, the PS_1, PS_2, and PS_3 amended STL soil increased in both θ_{pl} and θ_{ll} at 10% WBC relative to nonamended soil, which could be attributed to the high absorptive capacity of the amended soil for water due to the creation of pores by the incorporation of WBC particles in the soil. These pores would result in a WBC-amended soil requiring more water to behave in a plastic or liquid manner than the nonamended soil.

Penetration resistance and shear strength

The unamended STL soil compacted in the standard compaction Proctor mold (STL-25B) soil had a PR of 1,827±200 kPa; PR showed a decreasing trend with increasing WBC dosage and with finer particle size (Figure V.3). Thus, the highest WBC dosage with finest particle size lowered the PR to 610±124 kPa. The PR decreased than the nonamended soil for all the treatment but not for the PS3-2%. This decrease in PR is attributed to the decrease in the interparticle resistance and overburden pressure. All the curves exponentially decayed and appeared to plateau at the 10%

dosage for all particles sizes (Figure V.3), indicating that a PR lower than 610±124, 1206±173, or 1604±95 kPa could not be achieved with PS1, PS2, or PS3 amendment, respectively. At a 10% amendment rate, PR increased with increasing WBC particle size. The PR increased from 610±124, to 1604±95 kPa when the particle size of the WBC amended to the soil increased from PS_1 to PS_3, even though the ρ_{max} and θ_{opt} did not differ (Table V.2 and Figure V.3).

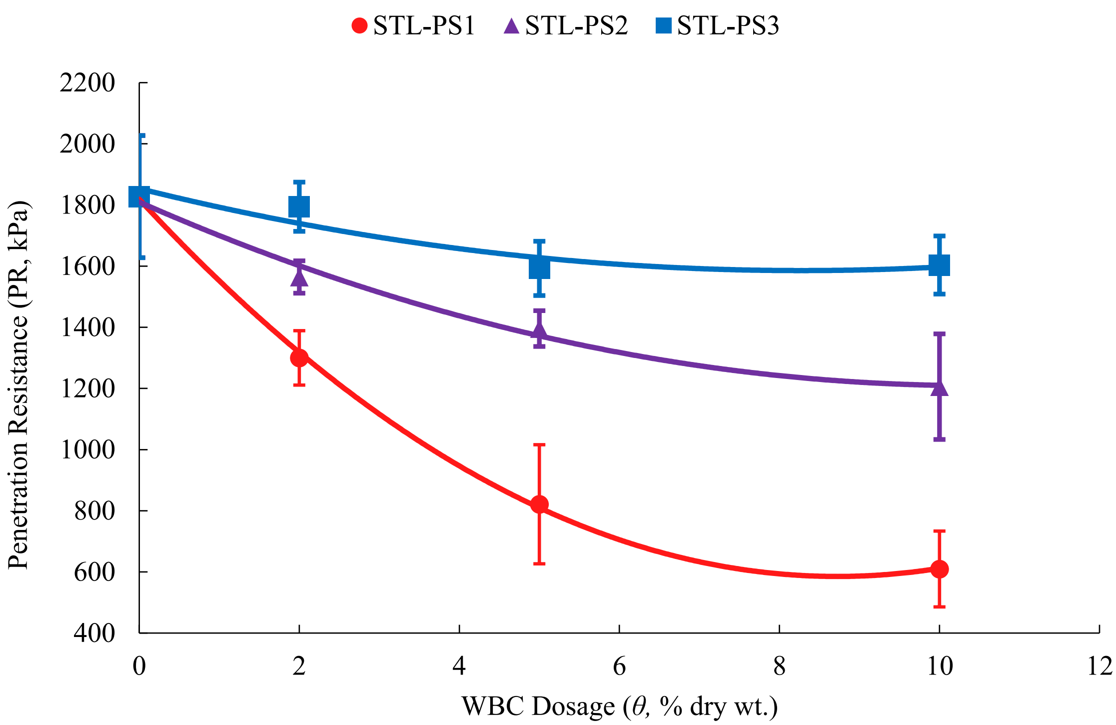

Figure V.3: Relationships between mean penetration resistance measured to 10 cm depth of a compacted silt loam (STL) soil and wood-derived biochar (WBC) dosage (2, 5 and 10%) of three WBC particle size ranges: 0.5–210 µm (PS_1), 210–420 µm (PS_2), and 420–841 µm (PS_3)

The compacted unamended STL (STL-25B) soil had a τ of 858±25 kPa; as with PR, τ showed a decreasing trend with increasing WBC dosage and with finer particle size (Figure V.4). Thus, the highest WBC dosage with finest particle size lowered the τ to 221±40 kPa. This decrease in τ is attributable to the reduced cohesion of soil particles amended with the carbonaceous material due to created pores. Also, the amended soil (10% PS_1) was compacted and θ_{opt} was 21±1.4%, whereas the nonamended soil was compacted and θ_{opt} was 16.5±0.4% (Table V.2). The differences in the moisture content (*θ)* of the soil when the shear vane test was conducted could have also contributed to the decrease in the $\mathcal{T}$ value of the compacted soil.

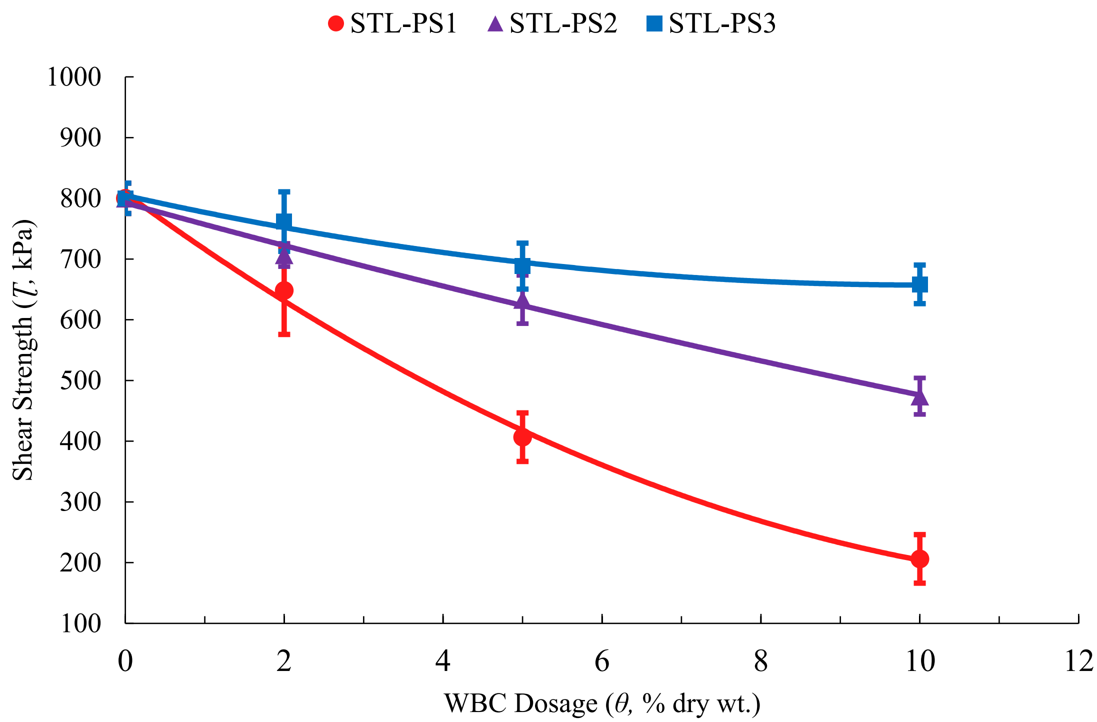

Figure V.4: Relationships between mean shear strength of a compacted silt loam (STL) soil and wood-derived biochar (WBC) dosage (2, 5 and 10%) of three WBC particle size ranges: 0.5–210 µm (PS_1), 210–420 µm (PS_2), and 420–841 µm (PS_3)

Conclusions

As the WBC dosages increased in the STL soil, WBC induced changes to soil ρ_o, ρ_{max} and θ_{opt}, *PI*, PR, and $\mathcal{T}$. No changes in the ρ_{max} or θ_{opt}, θ_{pl} were observed with differing WBC particle sizes at the same dosage. Further, at the high dosage (10%), the PR and $\mathcal{T}$ of the PS_1 amended soil was lower compared to relatively larger particles sizes (PS_2 and PS_3). These findings clearly indicate that varying the WBC particle size and dosage disrupts soil pore volume in a different manner.

The ρ provides a measure of how close the soil particles are packed, with no information on the geometric structure or the pore size distribution of the soil. The small particle sizes range of WBC could have created more pores and/or resulted in a variation in the moisture distribution, allowing the decrease in the PR compared to the soil amended with relatively large particle sizes.

1. In general, particle size of the WBC added to the STL soil influenced the soil mechanical impedance. Relatively fine WBC could have created more pores in the soil than the larger particles but did not show a difference in the bulk density because:
    a. Relatively fine WBC could be denser, due to the loss of WBC internal pores.
    b. Relatively smaller fine WBC particles occupied more places (spots) in a unit soil volume (because the % dose applied to a soil is based on weight, so as the particles becomes smaller their number in a unit volume becomes higher).
    c. As the WBC particles becomes finer, their shape could have changed from spherical to more platted.
2. The moisture in the soil could have been distributed unevenly in the soil matrix because WBC is less hydrophilic than the soil. The θ_{pl}, θ_{pl}, and θ_{opt} is calculated on a gravimetric moisture content dry basis.
3. The PR did not differ between the PS_2-5% and PS_1-2%, thus using PS_1 amendment could be more economical to reduce the PR of an agricultural STL soil because a smaller quantity is needed to produce the same decrease in PR. On the other hand, there will be less soil structural damage expected by external forces if larger particles sizes ranges of WBC are added because the *PI* of PS_2 was lower than PS_1. Increasing the *PI* means the range of moisture over which the soil is susceptible to compaction by external forces increases.

4. Before modeling techniques are employed, further investigations are required to fully assess the WBC effects on soil porosity and strength of amending different compaction-prone soils with WBC of various particle sizes and dosages. WBC particle sizes and dosages specific to a particular soil texture could then be quantified to develop a predictive model to optimize WBC particle size and dosage to improve soil mechanical properties, with little consequence on soil workability.

Connecting Text

Chapter V showed that WBC amendment significantly affects soil physico-mechanical characteristics. Therefore, in **Chapter VI,** two types of texturally contrasting soils were amended with two WBC particle sizes in a factorial design. The physico-mechanical characteristics of the amended soils were evaluated, in addition to select chemical properties.

Chapter VI

Influence of wood-derived biochar on the physico-mechanical and chemical characteristics of two texturally different agricultural soils

Abstract

Amendment of soils with biochar has been shown to enhance fertility and increase crop productivity, but the specific influence of biochar on soil compaction and workability remains unclear. Select physico-mechanical and chemical properties of clay loam and sandy loam soils were measured after amendment with wood-derived biochar (WBC) of two particle size ranges (0.5–420 µm and 420–841 µm) at five dosages ranging from 0.5 to 10% dry wt. Whereas the clay loam soil aggregate workability increased when the relatively fine WBC was applied at a rate 10%, soil fertility was not enhanced.

Keywords: Biochar, particle size, bulk density, Proctor compaction, plastic limit, liquid limit, soil workability, soil fertility.

Introduction

Biochar is produced by pyrolysis, a process whereby biomass is decomposed in the absence of oxygen at temperatures of 250–700°C (Yuan et al. 2014). Pyrolysis conditions and feedstock material influence the chemical composition and physical structure of biochar (Cimò et al. 2014). Wood-derived biochar (WBC) with particle diameters < 2,000 µm had skeletal and particle densities of 1.96 and 0.60 g/cm^3, respectively (Brewer et al. 2014; Mitchell et al. 2015), and a surface area of 75 m^2/g (Brewer et al. 2014). Application of 6% (dry wt.) WBC decreased the soil liquid limit (θ_{ll}; the θ at which the soil changes from a plastic state to a liquid state), increased the θ_{pl} (the θ at which the soil changes from a semi-solid state to a plastic state) and consequently decreased the plasticity index ($PI = \theta_{pl} - \theta_{ll}$) of a clayey soil (Zong et al. 2016). However, the effect on θ_{pl}, could become less significant as soil clay content increases, as noted by Qu et al. (2014) for rice-husk ash amendment. Amendment with 6% coal fly ash (particle size < 2 mm) decreased the θ_{ll} and increased the θ_{pl} of clay soil and led to a 35% decrease in soil *PI* (Lu et al. 2014).

Application of WBC to soils could alter soil workability (*W*), or the ease with which soil is manipulated during cultivation, as assessed through the soil dry aggregate tensile strength (σ_t)—the force per unit area required to disrupt the aggregate. Soil *W* is inversely linked to aggregate σ_t (Arthur et al. 2014) and directly linked to friability—the tendency of a mass of soil to crumble into smaller aggregates of certain size range under an applied stress (Utomo and Dexter 1981). Thus, *W* combines friability and the energy needed to fragment the soil clods. Friability could determine the damage done to the soil structure by tillage (Watts and Dexter 1998). The clay and silt contents greatly increase the σ_t of soils (Imhoff et al. 2002). Soil aggregate σ_t and friability are indications of soil structural quality (Reis et al. 2014). In addition, soil fertility has been shown to improve after WBC amendment; the degree of improvement depends on the amount of WBC applied and the incubation period of the mixture (Li et al. 2016).

Amended clayey soil showed lower cohesion (*c*) and higher angle of internal friction (ϕ) (Zong et al. 2016). Soil *c* is the result of the bonding between soil particles, whereas ϕ is the resistance to movement of soil particles when a shear force is applied. Such changes have implications in farm management, since WBC amendment can reduce soil shear strength (T) (Blanco-Moure et al. 2012; Zong et al. 2016). Zong et al. (2016) showed WBC (particle size < 2 mm) has a lower cohesion and greater angle of internal friction than a clay loam (CL) soil. Thus, a CL soil amended with 6% WBC had lower cohesion and a greater angle of internal friction. Also, the tensile strength (σ_t) of the soil decreased from 466 to 233 kPa. These changes were attributed to alteration in the soil pore structure and degree of water saturation of the soil. In another study, the σ_t of a clayey soil decreased from 937 to 354 kPa with 6% (dry wt.) WBC amendment (Lu et al. 2014).

The objective of this research project was to determine the effects of amendment with different particle sizes of WBC on the PI, compaction behavior, soil workability (*W)* and fertility (organic matter [OM] content, nutrient composition, and pH) of two soil types differing in texture: a sandy loam (SL) and a CL soil.

Methods

Shear strength parameters

The SL and CL soil shear parameters (*c* (kPa) and ϕ (º)) were determined by the standard shear box method ASTM D3080 / D3080M-11 (ASTM International 2011).

Soil friability and workability

Artificial soil aggregates were made by hand-rolling the soil at its θ_{opt} to three sizes, following the procedures outlined by Elmholt et al. (2008). The air-dried soil aggregate with a diameter of 30, 40 or 50 mm were crushed (Dexter and Kroesbergen 1985; Dexter and Bird 2000) using a universal testing machine (INSTRON Model 5565) with a constant speed of 4 mm/s. Equation VI.1 was used to calculate the tensile strength (σ_t; (kPa)) of each soil aggregate (Utomo and Dexter 1981):

$$\sigma_t = 0.576\ (P/d^2) \qquad \text{(Equation VI.1)}$$

Where, *P* is the polar force (N) needed to fracture the aggregate, and *d* is the mean aggregate diameter (m). 0.576 is the relationship between the compressive and tensile stress in the centre of the aggregate.

Soil *FI* values were calculated from the σ_t measurements of different aggregate sizes. The dimensionless friability index (*FI*) is estimated from the variation of tensile strength σ_{st} af all aggregates about their mean (σ_t^-), as shown in Equation VI.2 (Watts and Dexter 1998).

$$FI = \sigma_{st} / \sigma_t^- \qquad \text{(Equation VI.2)}$$

Where, σ_{st} is the standard deviation of the tensile strength of various aggregates sizes and σ_t^- is the total mean tensile strength of all aggregate sizes.

The lower the value of the *FI*, the greater strength of the smaller aggregate relative to the larger. If *FI* < 0.1, the soil aggregate is non-friable (i.e., cemented clay); if *FI* = 0.1–0.2, it is slightly friable; if *FI* = 0.2–0.5, it is friable; if *FI* = 0.5–0.8, it is very friable; and if *FI* ≥ 0.8, the aggregate is mechanically unstable (Imhoff et al. 2002).

The soil workability (W_{agg}), which depends on the middle sized aggregate 40 mm, is calculated as the ratio of friability to mean of the median aggregate ($\sigma_{t\text{-}40}$), as shown in Equation VI.3 (Arthur et al. 2014).

$$W_{agg}=FI/\sigma_{t\text{-}40} \quad \text{(Equation VI.3)}$$

Two soils with the same *FI* but smaller $\sigma_{t\text{-}40}$ have low W_{agg}, whereas soils with the same $\sigma_{t\text{-}40}$ but larger *FI* have high W_{agg}. Lower W_{agg} values indicate unsuitability of soil for fragmentation at a given energy input (Getahun et al. 2016).

Soil fertility

The OM, nutrient composition, and pH of soil, WBC, and soil-WBC mixtures were determined by dry combustion (Slepetiene et al. 2008), the Mehlich-3 extraction method (Mehlich 1984), and a pH meter (Carter 1993) respectively.

Results and Discussion

Particle size

The SL and CL soils were well-graded. The SL soil contained 5% clay, 20% silt, and 75% sand. By comparison, the CL soil contained 39% clay, 35% silt, and 26% sand. No evidence of soil texture modification was observed because of the WBC addition. Therefore the amended soils were still classified as SL and CL according to USDA-NRCS (2004).

Bulk density, maximum bulk density, and optimum moisture content

The θ_{opt} for the ρ_{max} was higher in the CL soil—with higher clay content—than the SL soil (Table VI.1), as reported by Larson et al. (1980), Craig (1974), and Barzegar et al. (2000). Therefore, the CL soil is more susceptible to compaction than the SL soil. The ρ_o of the unamended SL, unamended CL soil, $PS_{1,2}$ and PS_3 were 1.19±0.03, 0.99±0.04, 0.32±0.02, and 0.33±0.02 t/m^3, respectively. The ρ_o of the CL was lower than the SL soil, whereas the ρ_o of the $PS_{1,2}$ and PS_3 WBC did not differ (Table VI.1).

The θ_{opt} of the amended SL soil decreased with increasing dosages of either $PS_{1,2}$ or PS_3 WBC (Table VI.2 and Figure VI.2). At dosages of 0.5 and 1.75% of either particle size, θ_{opt} did not differ. The θ_{opt} of the SL-$PS_{1,2}$ treatment was higher than the SL-PS3 treatment at 3, 6 or 10%. On the other hand, the θ_{opt} of the CL-$PS_{1,2}$ treatment was higher than the untreated CL (θ_{opt} =16.7±0.4%) soil at 1.75, 3, 6, and 10% and for the CL-PS_3 at 3, 6 and 10%, respectively (Table VI.1 and Figure VI.3). The θ_{opt} for the CL-10%-$PS_{1,2}$ was near the CL-10%-PS_3 (not different with $p=0.078$); whereas SL-10%-$PS_{1,2}$ was higher than the SL-10%-PS_3 at all rates (differ with $p=0.0037$) (Table VI.2). The CL soil θ_{opt} increased after amendment of the $PS_{1,2}$ by 24 and 39% at 6 and 10%, and by about double these value in SL soils.

After SL amendment with $PS_{1,2}$, the mean ρ_o decreased by 4.2, 7.7, 10.7 and 14% at 3, 6 and 10% WBC dosages, respectively, and by 5.1, 6.4, 11.5 and 14.7% in CL soil, respectively (Table VI.3). The RID also decreased with increasing WBC dosage (Table V.3).

Table VI.1: Loose bulk density (ρ_o), maximum bulk density (ρ_{max}), relative increase in bulk density (RID = (($\rho_{max} - \rho_o$)/ ρ_o)×100), and optimum moisture content (θ_{opt}) of unamended sandy loam and clay loam soils

Soil Type	**Physical Properties**			
	ρ_o	ρ_{max}	RID	θ_{opt}
Sandy loam	1.19±0.03	1.68±0.03	41±4.0	11.9±0.7
Clay loam	0.99±0.04	1.56±0.01	58±3.7	16.7±0.4

Table VI.2: Mean ± standard deviation maximum bulk density (ρ_{max}), and optimum moisture content (θ_{opt}) of sandy loam (SL) and clay loam (CL) soils after wood-derived biochar (WBC) amendment at five dosages and two particle sizes

Soil type	**WBC dosage (% dry wt.)**	**WBC particle size**			
		0.5–420 μm ($PS_{1,2}$)		420–841 μm (PS_3)	
		ρ_{max} (t/m^3)	θ_{opt} (%)	ρ_{max} (t/m^3)	θ_{opt} (%)
SL	0.5	1.65±0.05a(a)	12±1.0a(a)	1.67±0.05a(a)	12±1.3a(a)
	1.75	***1.61***±0.05a(a)	12.8±1.2a(a)	***1.63***±0.04a(a)	12.3±1.2a(a)
	3	1.55±0.03a(b)	***15.0***±1.6a(b)	***1.59***±0.02a(b)	***13.8***±1.0b(b)
	6	***1.50***±0.06a(c)	***17.5***±1.7a(c)	***1.46***±0.02a(c)	***14.8***±1.4b(b)
	10	1.43±0.03a(d)	***18.9***±1.2a(d)	***1.45***±0.04a(c)	***15.8***±1.2b(c)
CL	0.5	1.55±0.01a(a)	17.1±1.9a(a)	1.54±0.04a(a)	16±0.4a(a)
	1.75	***1.48***±0.01a(b)	***18.5***±1.7a(ab)	***1.51***±0.03a(b)	17±1.9a(a)
	3	***1.46***±0.02a(b)	***19.5***±2.0a(bc)	***1.49***±0.02a(c)	***19***±1.9a(bc)
	6	1.38±0.02a(c)	***20.7***±2.0a(c)	***1.48***±0.01b(c)	***20***±1.9a(c)
	10	***1.33***±0.02a(d)	***23.2***±1.9a(d)	***1.42***±0.02b(d)	***21.5***±2.0a(c)

Values in bold italics differ ($p \leq 0.05$) from unamended soil. SL unamend CL unamend. Numbers followed by the same letter without parentheses implies no difference in the same row; whereas numbers followed by same letters with parentheses implies differences in the same column

Table VI.3: Mean ± standard deviation RID of two soil types after wood-derived biochar (WBC) amendment at five dosages and two particle sizes

Soil type	**WBC dosage (% dry wt.)**	**WBC particle size**			
		0.5–420 µm ($PS_{1,2}$)		420–841 µm (PS_3)	
		ρ_o (t/m^3)	RID (%)	ρ_o (t/m^3)	RID (%)
SL	0.5	1.19±0.02	39±5.1	1.19±0.02	40±4.6
	1.75	1.19±0.03	34±4.0	1.19±0.02	38±6.7
	3	***1.16***±0.01	34±4.0	1.14±0.02	39±4.5
	6	***1.15***±0.04	30±3.0	***1.12***±0.01	30±3.2
	10	***1.15***±0.03	22±2.1	***1.12***±0.01	26±3.3
CL	0.5	0.94±0.04	65±8.7	0.98±0.02	57±5.7
	1.75	0.91±0.02	63±6.3	0.97±0.03	56±5.4
	3	***0.89***±0.02	64±4.6	0.92±0.01	62±4.7
	6	***0.86***±0.03	60±4.6	0.93±0.02	59±5.2
	10	***0.86***±0.02	55±5.0	0.93±0.01	53±6.3

Values in bold italics differ ($p \leq 0.05$) from unamended soil.

Table VI.4: Mean ± standard deviation plastic limit (θ_{pl}), liquid limit (θ_{ll}), and plasticity index (PI) of clay loam soil after wood-derived biochar (WBC) amendment at five dosages and two particle sizes, as well as change in plasticity index relative to unamended

WBC dosage (% dry wt.)	**WBC particle size**							
	0.5–420 µm ($PS_{1,2}$)				420–841 µm (PS_3)			
	θ_{pl} (%)	θ_{ll} (%)	*PI* (%)	Δ*PI* (%)*	θ_{pl} (%)	θ_{ll} (%)	*PI* (%)	Δ*PI* (%)*
0.5	20.8±2.3a(a)	49.3±2.8a(a)	28.5±0.6a(a)	8.5	20.2±2.1a(a)	50.0±2.3a(a)	***29.8***±2.2a(a)	13.7
1.75	21.8±1.0a(a)	50±2.5a(a)	28.2±1.6a(a)	7.6	21±2.0a(a)	48.9±2.3a(a)	27.9±2.4a(b)	6.5
3	***23.9***±1.8a(b)	***55.7***±2.3a(b)	***31.8***±2.1a(b)	21.4	21±1.8b(a)	***52***±2.2b(ab)	***31.0***±2.1a(a)	18.3
6	***25***±2.0a(b)	***57.6***±2.5a(b)	***32.6***±2.3a(b)	24.4	***23.6***±1.3a(b)	***53.3***±2.1b(bc)	***29.7***±3.4a(a)	13.3
10	***26.2***±2.0a(c)	***59.7***±2.0a(c)	***33.5***±2.3a(b)	27.8	***24.8***±2.4a(b)	***54.8***±2.0b(c)	***30***±2.4a(a)	14.5

* Relative % difference

Values in italics differ ($p \leq 0.05$) from unamended soil, whose θ_{pl}, θ_{ll} and *PI* were 21.9±2.3, 48.2±3.3, and 26.2±2.9%, respectively

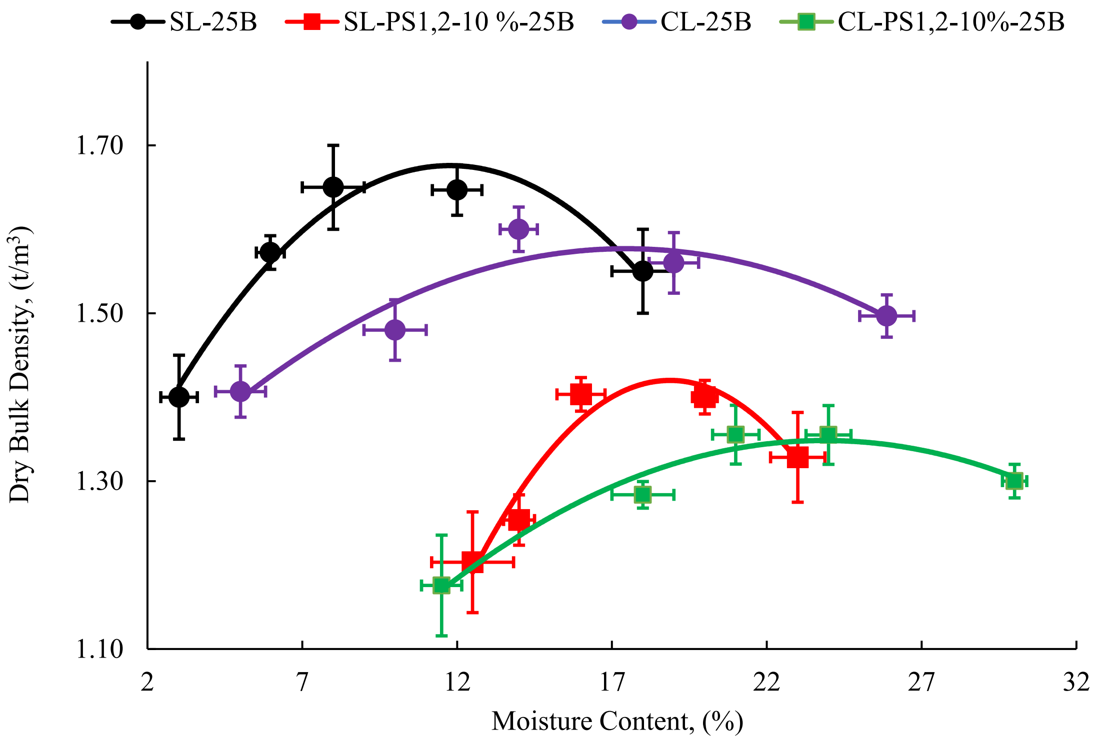

Figure VI.1: Compaction curves, 25 blows (25B) for sandy loam (SL) and clay loam (CL) soils before and after amendment with 10% 0.5–420 µm ($PS_{1,2}$) wood-derived biochar

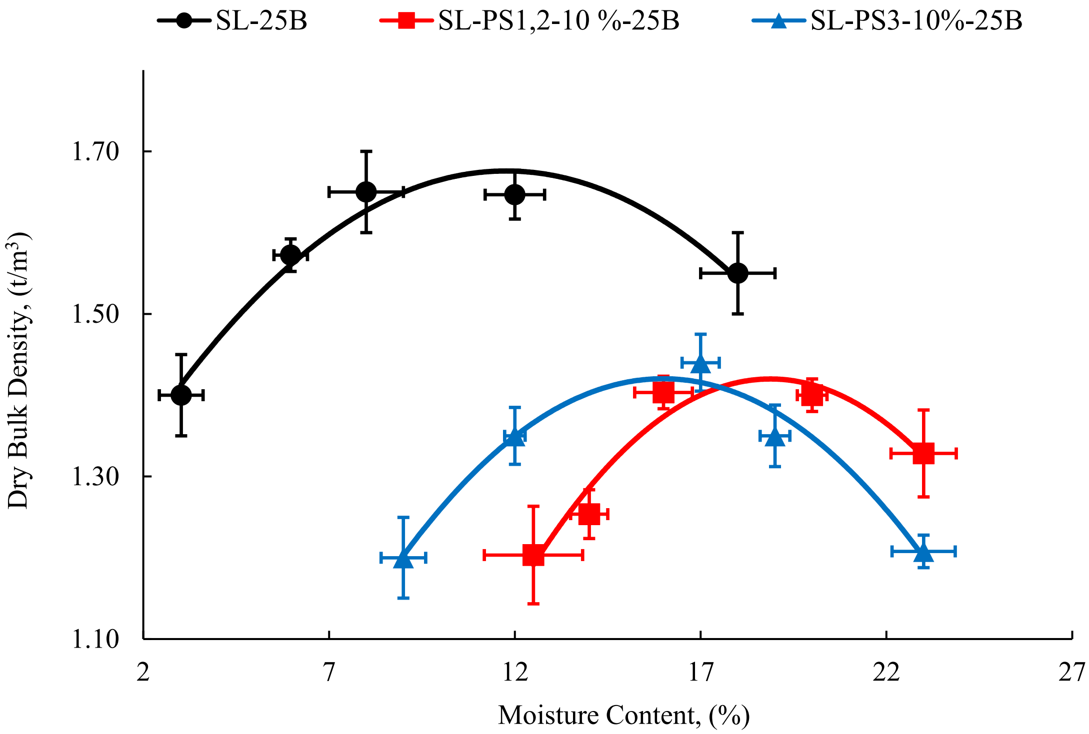

Figure VI.2: Compaction curves, 25 blows (25B) for sandy loam (SL) soil before and after amendment with 10% 0.5–420 µm ($PS_{1,2}$) and 420–8541 µm (PS_3) wood-derived biochar

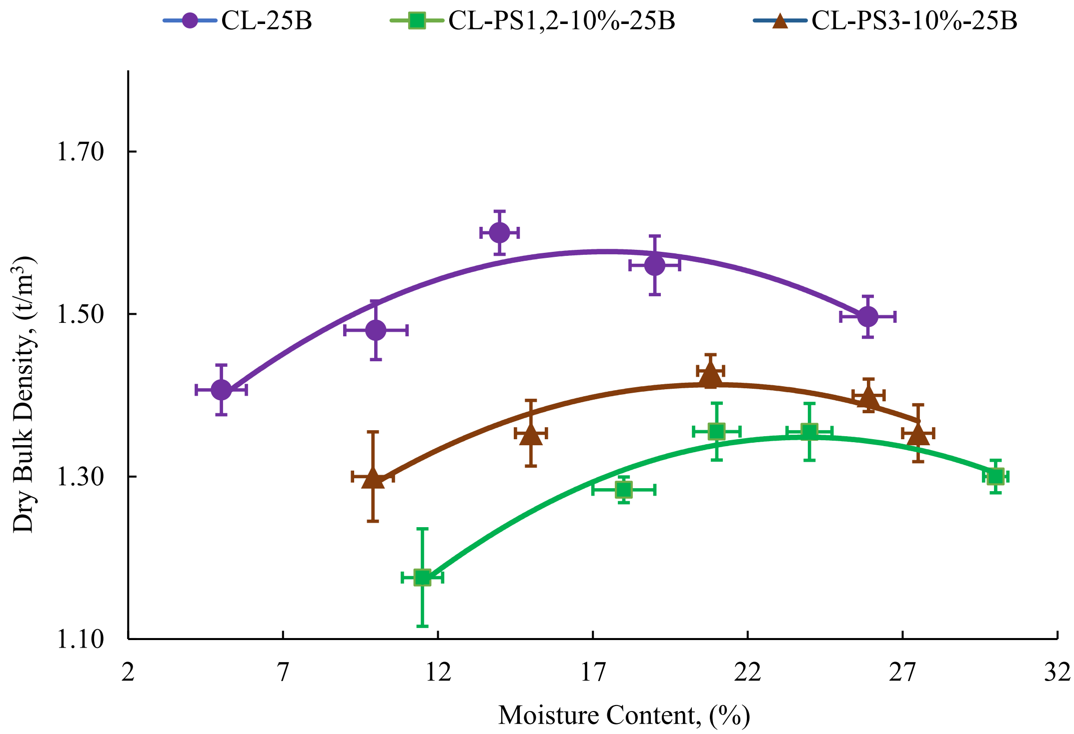

Figure VI.3: Compaction curves, 25 blows (25B) for clay loam (CL) soil before and after amendment with 10% 0.5–420 µm ($PS_{1,2}$) and 420–841 µm (PS_3) wood-derived biochar

As the soil texture changes, the compaction curves exhibit different trends when amended with varying particle sizes of WBC (Figure VI.1, Figure VI.2, Figure VI.3, and Table VI.2). This difference in response related to soil texture could be attributed to the fact that the larger SL soil pores could accommodate more WBC particles, resulting in a significant increase in the θ_{opt} and no change in the ρ_{max} when relatively coarse particles are added (The ρ_{max} of both amended SL soils with $PS_{1,2}$ or PS_3 are less than the unamended SL soil; The θ_{opt} of both amended SL soils with $PS_{1,2}$ or PS_3 are higher than the unamended SL soil); whereas the CL soil pores have relatively higher volume of small pores compared to the SL soil, which could result in the lack of response in the θ_{opt} but a decrease in the ρ_{max} with relatively fine WBC amendments (The ρ_{max} of both amended CL soils with $PS_{1,2}$ or PS_3 are less than the unamended CL soil).

The θ_{opt} for the CL-$PS_{1,2}$-10%-5B (θ_{opt} = 23.9%) was slightly higher (differ with $p=0.03$) than the CL-PS_3-10%-5B (θ_{opt} =20.2%) and the CL-PS_3-10%-5B was higher than the untreated CL-5B (θ_{opt} =17.4%) soil. In the SL soil (SL-5B; θ_{opt} =11.8%) the case of the changes in the θ_{opt} was not the same trend as the CL-5B when amended with different WBC particle sizes. The SL-$PS_{1,2}$-10%-5B and SL-PS_3-10%-5B had different θ_{opt} of 18.5% and 15.8% respectively. The density was not different possibly because relatively fine WBC incorporated in SL soil conferred resistance to compaction and/or the presence per unit volume was less for the PS_3 compared to $PS_{1,2}$. In addition, the creation of new pores by WBC in the soil matrix, whether the particles of WBC occupied the pore spaces ($PS_{1,2}$) or took the place of soil particles (PS_3), the low WBC particle density (0.7 g/cm^3) relative to soil particles (2.65 g/cm^3); (MacRae and Mehuys, 1985), and the variation on the paritcle density of WBC, which decreases as particles increases-due to lost pores-, likely contributed to the treated SL soil with different particle sizes have the same ρ_{max} but different θ_{opt}.

Plasticity index

The θ_{pl}, θ_{ll}, and PI of the unamended CL soil were 21.9±2.3%, 48.2±3.3%, and 26.2±2.9%, respectively, whereas the SL soil showed no plasticity, however the θ_{ll} for the 0.5, 1.75, 3, 6, and 10% SL-$PS_{1,2}$ were 26.5±3.1%, 27±2.2%, 28.4±2.7%, 32±3.2%, 39±4.1%, and for and SL-PS_3 were 42±2.9% and 26.5±2.4%, 26.5±2.1%, 27±3.0%, 29±3.0%, 35±4.0%, and 40±2.7%, respectively. Amendment of the CL soil with 3, 6, or 10% of the $PS_{1,2}$ increased the PI by relative values of 21.4, 24.4 and 27.8%, respectively, relative to unamended soil. The θ_{ll} values for the same $PS_{1,2}$ amendments increased with an increase in the application doses. For the same amendment dosages, both $PS_{1,2}$ and PS_3 amendments led to an increase in the PI. The PI value in the $PS_{1,2}$ and PS_3 amended CL soil did not differ. Further, the effect of increasing the WBC-PS_3 application dose on the CL soil PI was not consistent. Given the important role of the value of the

θ_{ll} on the *PI*, the similarity of the *PI* response can be attributed to the relatively small increase in θ_{pl} of the PS_3 amended soils compared to that of the $PS_{1,2}$. The increase in θ_{pl} for the $PS_{1,2}$ was significant at 3, 6 and 10% amendment dosages only, whereas, the increase in θ_{ll} for the $PS_{1,2}$ amendment was greater than that for PS_3 amendments. This inconsistency minimized the differences in the *PI* values of the soils amended with $PS_{1,2}$ and PS_3 WBC. Since clayey soils exhibit high plasticity and are therefore highly prone to compaction (Mapfumo and Chanasyk, 1998a), the CL soil amended with WBC has higher *PI*—given the larger moisture range within which deformation could occur—is not more prone to compaction than unamended soil. These results suggest that addition of different particle sizes of WBC to CL soil will not change the workable range of the soil (Figure VI.3) and the density of the soil decreases with increasing the amendment dose of the WBC.

The unamended CL soil had an θ_{opt}/θ_{pl} of 0.76±0.06. This ratio increased to 0.88±0.17 for the 10% amendment with no difference between the means for different particle sizes. This analysis clearly indicates that the addition of WBC to the CL soil will decrease the θ_{pl} over the θ_{opt} and could render soil more prone to compaction, regardless of the particle sizes.

Soil shear strength

Untreated SL soil had 62% lower *c* than CL soil (14.90±0.98 and 39.17±1.31 kPa for SL and CL soil, respectively). The 6 and 10% $PS_{1,2}$ amended CL soils had lower *c* values than unamended CL soils, whereas the 3, 6, and 10% $PS_{1,2}$ amended SL soils had lower *c* values than unamended SL soils (Figure VI.4). No differences were observed between the unamended soils and the PS_3 amendment SL soil, but a decrease in the soil cohesion was seen in 6 and 10% amended CL soil.

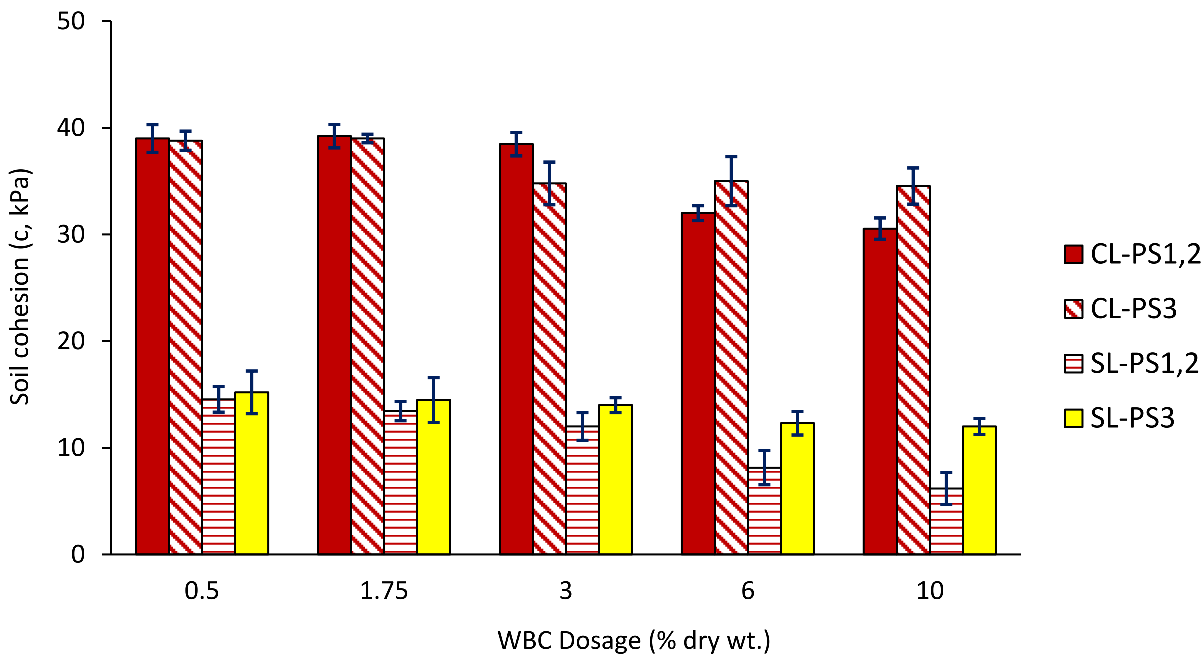

Figure VI.4: Soil cohesion of sandy loam (SL) and clay loam (CL) soils amended with 0.5 to 10% (dry wt) fine (0.5–420 µm; $PS_{1,2}$) or coarse (420–841 µm; PS_3) wood-derived biochar (WBC)

Untreated SL soil had 35.3% higher ϕ than CL soil (40.03±2.4° and 29.67±1.53° for SL and CL, respectively).

Compared to an unamended SL, an increase in ϕ was found upon amendment of the soil with $PS_{1,2}$ at dosages of 6 and 10% (dry wt.) and with PS_3 at a dosage of 10%. There was an increase in the ϕ of the CL soil when it was amended with $PS_{1,2}$ WBC at dosages of 6 and 10%.

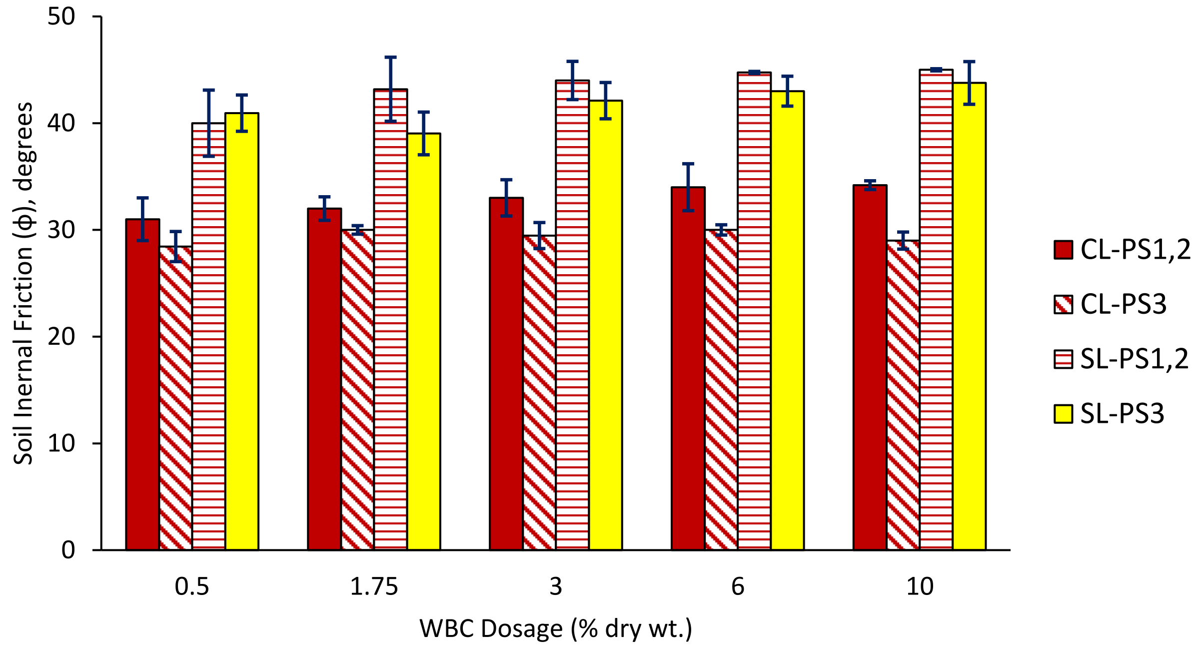

Figure VI.5: Influence of the amendment of the SL and CL soils with different rates (% dry wt.) of small ($PS_{1,2}$) or large (PS_3) particle size WBC on soil internal friction

Given the influence on soil failure in front of a tillage tool and the thrust force under tractor tires, a decrease in the soil *c* and an increase in soil *ϕ* would require altering agricultural machinery and practices. For example, since an increase in *ϕ* would be beneficial under high tractor loads, amendment with finer WBC would be recommended when heavy tractors are used (large-scale farms). Conversely, a decrease in the soil *c* would require wider tractor tires to overcome the reduced soil *c*. Therefore, relatively coarse WBC amendment would be recommended in small-scale farms or wider wheels if smaller WBC particle sizes are applied. Conversely, in front of a tillage tool, the force required to cut the soil will be reduced when finer WBC is applied to CL soil at dosages of 6 or 10%. This is because a decrease in the value of *c* and *ϕ* would have a minimal effect on the cutting action.

Tensile strength of soil aggregates

Untreated CL soil aggregates exhibited nearly 10-fold higher σ_t than SL soil aggregates (1489±128 kPa and 152±67 kPa for the CL and SL, respectively). Addition of $PS_{1,2}$ at dosages of 1.75–10% reduced the mean σ_t of CL soil aggregates by 17–47%, with the maximum change observed for the 10% treatment and no changes in the 0.5% $PS_{1,2}$ (Figure VI.6). For the coarser WBC, only the 6 and 10% treatments decreased the mean σ_t in the CL soil. By comparison, the σ_t of SL soil aggregates was less sensitive to WBC amendment, only showing a decrease at 6 and 10% amendment with $PS_{1,2}$ and no change with PS_3.

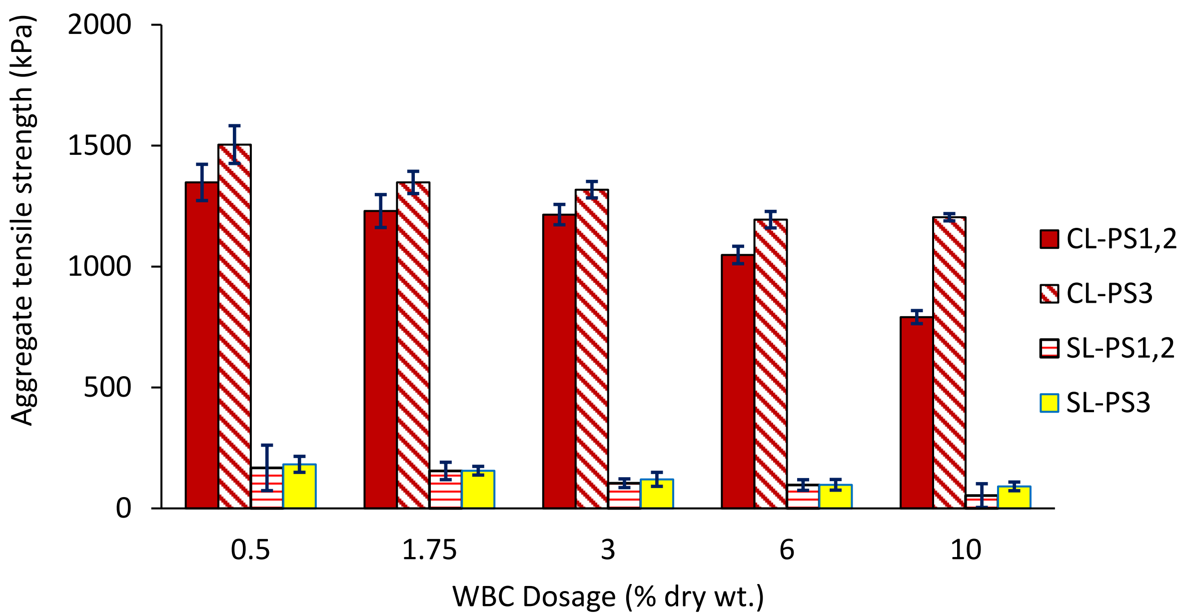

Figure VI.6: Aggregate tensile strength (σ_t) of CL soil amended at different rates with small particle size ($PS_{1,2}$) and large particle size (PS_3) WBC

Soil friability index

The *FI* of untreated CL meant it was classified as non-friable. The *FI* of the CL soil was nearly 8-fold higher than the *FI* of untreated SL soil. The 10% $PS_{1,2}$ amendment increased the *FI* of CL soil to slightly-friable, but did not change the *FI* of SL soil. By comparison, the 10% $PS_{1,2}$ amendment did not change the *FI* of CL or SL. Friability and aggregate σ_t are an indication of soil W_{agg}. Therefore, the CL soil W_{agg} increased from 5×10^{-5} kPa^{-1} to 29×10^{-5} kPa^{-1} with the application of 10% $PS_{1,2}$, and to 18×10^{-5} kPa^{-1} with the application of 10% PS_3. The CL-$PS_{1,2}$ had the same friability as the CL-PS_3, but higher workability. Therefore, the CL-PS_3 would be easier to till because clay disperses in water and when dried, will either flocculate (if OM concentrations are high) or form internal crust face-to-face cement (if OM concentrations are low). Internal crust formation will result in stronger aggregates, which consequently reduces soil friability and making soil less workable (Getahun, 2016). Therefore, applying relatively fine WBC to CL soil will increase soil W_{agg} and make it easier to manipulate during cultivation. There was no difference in the SL soil W_{agg} at any WBC dosage or particle sizes.

Table VI.5: Friability index (FI), Tensile strength (σ_t), aggregate workability (W_{agg}), and classification, of clay loam (CL) soil amended with 10% wood-derived biochar with particle sizes of 0.5–420 µm ($PS_{1,2}$) and 420–841 µm (PS_3)

Soil	*FI*	σ_t	W_{agg} $*10^{-5}$	Classification
CL	0.08(a)	1,517(a)	5(a)	Non-friable
CL-$PS_{1,2}$	0.11(b)	427(b)	29(b)	Slightly friable
CL-PS_3	0.10(b)	1204(c)	18(c)	Slightly friable

Numbers followed by same letters with parentheses implies differences in the same column

Biochar chemical composition and soil fertility

The pH of the WBCs of different particle sizes did not differ, but the finer WBC had higher soluble P, K, Ca and Mg concentrations than coarser WBC (Table VI.6). This difference in nutrient release is attributed to the relatively high surface area or the exposure of smaller internal pores in the finer WBC. The unamended SL soil had a higher pH, P and Al but lower K and Mg concentrations than the unamended CL soil (Table VI.6).

In CL and the SL soils amended with WBC at various dosages of either $PS_{1,2}$ or PS_3, the pH did not change (Table VI.6). On the other hand, the K concentrations increased when 10% $PS_{1,2}$ or PS_3

were added to the SL soil (Table VI.6). By comparison, Li et al. (2016) found the OM content of CL soil increased from 21.5 to 36.26 g/kg, and the available P and K showed no significant changes when 2% WBC was amended to the soil and the mixture was incubated for 135 days. However, Lehmann et al. (2003), Novak et al. (2009), Steiner et al. (2008), and Zong et al. (2016) reported that WBC addition to soil increased soil pH, and total C and available K and P concentrations. These differences could be attributed to the incubation period of different studies.

Table VI.6: Chemical composition of wood-derived biochar (WBC) of two particle size ranges and of sandy loam and clay loam soils

Treatment	Particle size range	pH	OM (%)	P	K	Ca	Mg	Al
				mg/kg				
WBC	0.5-420 µm	8	NA	65.5	783	1353	95.6	96.4
	420-841 µm	7.9	NA	28	527	626	53.5	126
Soil	Sandy loam	6.3	4.1	148	31	1316	79.4	1369
	Clay loam	5.8	5.4	66	135	1318	251	1143

Table VI.7: pH, phosphorus (P), potassium (K), calcium (Ca), magnesium, (Mg) and aluminum (Al) concentrations in two soil types after wood-derived biochar (WBC) amendment at different dosages and two particle sizes. Chemical composition of mixtures of WBC of two particle sizes. Chemical composition of mixtures of WBC of two particle size ranges, applied at different rates to the sandy loam or clay loam soils

Soil type	**WBC dosage (% dry wt.)**	**WBC particle size**											
		0.5–420 µm ($PS_{1,2}$)						420–841 µm (PS_3)					
		pH	P	K	Ca	Mg	Al	pH	P	K	Ca	Mg	Al
		(mg/kg)						(mg/kg)					
Sandy loam	3	6.6	150.0	39.5	1326	73.0	1332	6.4	157	29.4	1319	76.1	1372
	6	6.6	164.4	42.4	1340	71.2	1476	6.3	184.6	43.8	1360	50.4	1509
	10	6.7	154.2	***67.6***	1340	76.8	1391	6.6	175.4	***46.2***	1343	52.1	1426
Clay loam	3	5.7	47.0	114	1323	241.5	1094	5.8	48.8	125.0	1298	240.6	1105
	6	5.8	47.8	123.2	1331	237.4	1119	5.8	46.9	125.2	1304	236.8	1071
	10	5.8	52.5	135.5	1323	234.6	1096	5.7	47.3	125.6	1288	228.5	1060

Conclusions

1. WBC amendment increased the *PI* of the CL soil, thereby increasing the range of moisture within which the soil is most susceptible to compaction. This in turn–decreased the workable range of the CL soil under tillage operations because of structural damage to the soil. This was attributed to WBC addition decreasing the ρ_{max} of the CL soil, which ameliorates the effects of compaction. Further, the WBC-amended CL soil became more plastic, even though WBC itself is non-plastic (Brewer et al. 2013). Therefore, the increase in θ_{pl} and θ_{ll} of CL soil amended with WBC could be attributed to a higher affinity of WBC-amended soil for water, which could result in WBC-amended soil requiring more water to behave in a plastic or liquid manner. Moreover, the water content of θ_{pl} did not change over the θ_{opt}, which may imply that soil could exhibit the same deformation and a similar workable range.
2. Unlike the STL (Chapter V) where the ρ_{max} and θ_{opt} were the same when amended with WBC of different particle sizes, the amended SL soil had the same ρ_{max} but lower θ_{opt} with relatively coarse WBC. The amended CL soil had the same θ_{opt} but lower ρ_{max} with relatively fine WBC. These findings are helpful because as the particle sizes of WBC changes, it clearly changes the behavior of the soil under compaction and influences the soil pore structure differently. These findings are useful in deciding the particle size of WBC that best suits a specific soil texture prone to compaction (i.e., clayey vs sandy soil). However, this decision will also depend on how the variation in WBC particle sizes affect pore water volumes and the soil penetration resistance. These are the objectives of Chapter VII and Chapter VIII, respectively.

3. WBC addition could enhance soil W_{agg}, depending on the WBC particle size. The W_{agg} increased when relatively fine WBC was applied to CL soil at dosages of 6 or 10%. WBC addition had no influence on the W_{agg} of SL soil, which had a very low *FI*. It is therefore recommended that finer WBC is applied to a CL soil with low friability.
4. The soil fertility was not affected by changes in WBC particle size. This was surprising, given that the WBC contained higher nutrient concentrations than the soils and finer particle release more nutrients than coarse particles.
5. The moisture in the soil could have been distributed unevenly in the soil matrix because WBC is less hydrophilic than the soil. The θ_{pl}, θ_{pl}, and θ_{opt} is calculated on a gravimetric moisture content dry basis. Since the WBC amended CL soil is less dense than the amended CL soil, therefore the θ_{pl} and θ_{opt} values will be relatively higher than the unamended soil.

Chapter VII

The impact of wood-derived biochar on the hydraulic characteristics of two texturally contrasting compacted agricultural soils: Implications on carbon sequestration

Abstract

Addition of biochar—charcoal produced through pyrolysis or gasification of biomass under anaerobic conditions—is often proposed to increase agricultural soil quality and crop yield, while at the same time sequestering carbon (C) from the atmosphere to help mitigate global climate change. From soil water retention curves (SWRCs) and saturated hydraulic conductivity (k_{sat}) analysis, the pore-size distribution and unsaturated hydraulic conductivity (k_{unsat}) of soils amended with varying dosages (0.5–10%) and two particle sizes (0.5–420 μm ($PS_{1,2}$) or 420–841 μm (PS_3)) of wood-derived biochar (WBC) were investigated under compacted conditions for sandy loam (SL) and clay loam (CL) soils. Amending a SL soil with 10% $PS_{1,2}$, compacted with five Proctor rammer blows, caused the volumetric field capacity (FC) and available water capacity (AWC) to increase from 15.8 to 24% and from 6.5 to 14.3%, respectively. In compacted SL, volume of the soil fissures and transmission pores (TPs) decreased, while the volume of storage pores (SPs) increased with increasing WBC dosage. The estimated k_{unsat} from the k_{sat} and SWRCs of the amended SL decreased from 0.40 to 0.13 mm/h. Only at 6 and 10% amendment with coarser WBC did the k_{sat} of the SL soil decrease (by 41 and 56%, respectively). CL soil amended with 10% $PS_{1,2}$ compacted with five Proctor rammer blows soil showed no changes in the FC and AWC. The compacted CL soil had a total pore volume of 47.9%, which increased to 52.6% with amendment of $PS_{1,2}$ WBC. Only 23.1% of the volume of the compacted CL were SPs; this value increased to 27.4% upon amendment with $PS_{1,2}$. The total pore volume, fissures, TPs and SP did not show any change with amendment of PS_3 WBC. The estimated k_{unsat} from the k_{sat} and SWRCs of the amended

CL soil increased from 0.06 to 0.13mm/h when the CL soil was amended with 10% $PS_{1,2}$. The WBC particle size and soil texture influenced the soil hydraulic characteristics such as the volume of the soil pores and the water flow inside the soil. Further, a simulation study to assess the potential soil-sequestered C in simulated agricultural fields due to changes in the soils bulk density, k_{sat}, and water retention (corresponding to a 10% $PS_{1,2}$ amendment rate) revealed that the SL soil C emissions will decrease by 0.071 tC/ha/y; whereas CL soil C emissions will decrease by 0.091 tC/ha/y.

Keywords: soil water retention, soil hydraulic conductivity, soil pore size distribution, soil carbon sequestration

Introduction

Amendment of soil with biochar—charcoal produced through pyrolysis or gasification of biomass under anaerobic conditions—improves soil structure and creates pores (Atkinson et al. 2010; Downie et al. 2009; Hardie et al. 2014; Major et al. 2009; Sohi et al. 2010; Verheijen et al. 2010). Soils amended with biochar show an increase in the surface area and porosity, and a reduction in density (ρ) (Abel et al. 2013; Eastman 2011; Hardie et al. 2014; Herath et al. 2013; Jien and Wang 2013; Laird et al. 2010; Liang et al. 2006; Masulili et al. 2010; Mukherjee and Lal 2013; Oguntunde et al. 2008). Therefore, the soil hydrological characteristics such as available water capacity (AWC), soil moisture retention, and hydraulic conductivity are improved by biochar amendment (Abel et al. 2013; Akhtar et al. 2014; Eastman 2011; Hardie et al. 2014; Herath et al. 2013; Jien and Wang 2013; Lim et al. 2016; Liu et al. 2012; Uzoma et al. 2011b). However, the influence of biochar on soil AWC is not always positive (Hardie et al. 2014). Tryon (1948) and Mukherjee and Lal (2013) observed a decrease in AWC when biochar was applied in powdered form to fine-textured soils. The direct contribution of biochar to soil hydraulic properties as a consequence of its intrinsic characteristics is also documented in the literature (Andrenelli et al. 2016; Baronti et al. 2014; Downie et al. 2009; Novak et al. 2012).

Despite the growing number of studies on the influence of biochar on the agricultural soil hydraulic characteristics, the influence of particle size of wood-derived biochar (WBC) on soil pore size distribution and unsaturated hydraulic conductivity (k_{unsat}) remain unclear, especially for compacted agricultural soils. Wang et al. (2016) demonstrated that the pore size distribution measured by mercury intrusion porosimetry and the pressure plate test method match well.

WBC amendment can also allow the soil to serve as a carbon (C) sink to aid in climate change mitigation. According to Lal (2007): "Terrestrial carbon (C) sequestration can be defined as the capture and secure storage of atmospheric C into biotic and pedologic C pools that would otherwise be emitted to or remain in the atmosphere." The global mean soil storage rate in agricultural soils is estimated to be 1 tC/ha/y (Smith 2016). Biochar applied at a depth of 30 cm to an agricultural farm can potentially offset up to 12% of equivalent emission from the farm (Woolf et al. 2010). WBC has an aromatic structure resistant to microbial degradation and therefore a higher potential for C sequestration (Brewer et al. 2011; Hansen et al. 2015; Lehmann et al. 2006; Smith et al. 2016). Sequestering C in soils could significantly reduce atmospheric CO_2 concentrations (Smith et al. 1997). The potential for negative emissions from soil C sequestration due to the enhanced hydraulic characteristics of the soils is still unclear.

Agricultural soils are degraded by depletion of organic C. Incorporating biochar into agricultural soils may restore the soil organic C content, thereby improving soil fertility (Hansen et al. 2015; Lal 2009) and increasing crop yields (Jeffery et al. 2011). A one tC/ha increase in soil C storage increased wheat yield by 4 t/ha (Lal 2004). Biochar also contributes to the cation exchange capacity (CEC) of soil, which is vital for nutrient retention (Abdollahi et al. 2014).

The first objective of this study was to investigate water retention and flow through compacted agricultural soils amended with WBC of two particle sizes (0.5–420 µm and 420–841 µm) through the assessment of soil pore size distribution. The second objective was to simulate the effect of soil amendment with WBC on the amount of C sequestered in the soil due to altered soil hydraulic characteristics and bulk density.

Methods

Soil water retention analysis

Soils were wetted to reach θ_{opt} then compacted in the Proctor compaction mold with either 5B, 10B or 15B. Samples were taken from the compaction mold for measuring the soil water retention in the pressure plates.

To obtain the SWRCs and to determine the soil FC and permanent wilting point (PWP) moisture contents, the soil water content at saturation and at eight soil matric potentials (also known as hydraulic head h) (–10, –33, –70, –100, –300, –500, –1,000, and –1,500 kPa) were determined with a pressure plate extractor as described by Cornelis et al. (2005). The moisture content at each h was expressed as a percentage by weight of dry soil (θ_d) which was then used to convert the θ_d data to a volumetric basis (v) according to Equation (VII.1) (Gardner, 1986):

$$v = \theta_d (\rho/\rho_w) \qquad \text{(Equation VII.1)}$$

Where ρ_w is the density of water.

The retention data at field capacity moisture content (FC) and PWP were determined at –30 and –1,500 kPa matric potentials, respectively, and were used to determine the AWC (FC–PWP) of each sample.

Soil pore-size-distribution

The Van Genuchten (1980) model was chosen to simulate the water flow process in the soil (Equation VII.2). The data from the water retention were fitted with the hydrologic software RETC (U.S. Salinity Laboratory, Riverside, California) to determine the shape parameters of the SWRC ($\alpha(1/kPa)$, n and m) and residual water content (θ_r) (Leij et al. 1992).

$$S_e = 1/\{1+(\alpha|h|)^n\}^m \qquad \text{(Equation VII.2)}$$

Where S_e is the soil degree of saturation = $(v - v_r) / (v_s - v_r)$; v_s is the soil volumetric moisture content at saturation (%); and v is the volumetric soil moisture content at |h| suction pressure (kPa) The reciprocal of α accounts for the air entry pressure, whereas n represents the slope of the curve, which increases as the soil texture becomes coarser. According to Mualem (1976), to reduce the number of parameters estimated by the RETC code and to simplify Equation VII.2, m is set to equal $[1 - (1/n)]$. The root-mean-square error (RMSE) between the model prediction and the observed water retention data is minimized through RETC software as a fitting process using the least square approach described by Marquardt (1963).

The pore-size-distribution was determined following the simplified Young-Laplace (Batchelor, 1967) as in Equation VII.3:

$$D = 30/|h| \qquad \text{(Equation VII.3)}$$

Where, D is the equivalent diameter of cylindrical pores in µm and h is the matric potential expressed in meters of water (m_w) (m_w=10^{-1} kPa). Therefore, the fissure (FS) D is greater than 500 µm ($h \leq -0.06$ m_w), the TP D is 50–500 µm ($-0.06 < h \leq -1.6$ m_w), the SP D is 0.5–50 µm ($-1.6 < h \leq -60$ m_w), and the residual pore (RP) D is less than 0.5 µm ($h > -60$ m_w) (Greenland, 1977). The volumetric moisture content (v; (%)) in each pore class was determined by substituting Equations VII.1 to VII.3 as follows:

$$v = \left\{\left[\frac{1}{(1 + [\propto \{30/D\}/c]^n)^m}\right] [v_s - v_r]\right\} + v_r \qquad \text{(Equation VII. 4)}$$

The v of the Fissures, TP, SP, RP, FC, and PWP were determined by Equation VII.4

Where, c is the conversion constant 0.1019 from kPa to m_{water}.

Soil hydraulic conductivity

The experimental procedures of Shukla et al. (2004) were followed for measuring the saturated hydraulic conductivity (k_{sat}) of a disturbed soil sample in the laboratory. The relative hydraulic conductivity (k_r) was determined by Equation VII.5 (Van Genuchten, 1980):

$$k_r(h) = \frac{1 - \{[\propto h]^{n-2}(1 + [\propto h]^n)^{-m}\}}{(1 + [\propto h]^n)^{2m}} \qquad \text{(Equation VII. 5)}$$

In this study, the k_r was determined at the θ of the FC (h = –30 kPa). The k_{unsat} was obtained by multiplying the laboratory measured k_{sat} by k_r (Van Genuchten 1980).

Soil carbon sequestration potential

The Environmental Policy Integrated Climate (EPIC) is a field-scale model designed to simulate surface runoff, nutrient immobilization and uptake, and crop yield of drainage fields. EPIC accounts for losses of C and N by leaching or volatilization of gaseous forms. The model calculates the movement of organic matter (OM) from surface litter to deeper soil subsurface layers and the resulting changes in C and N concentrations. The Century-EPIC simulation software calculates the

C sequestration potential of the soils from C mineralization rates. The CO_2 evolved during C mineralization has been used to determine the size of the functional pools of soil C (Jiang et al. 2013). Based on climatic variables, soil properties, C concentration, and crop growth characteristics, the model projects the amount of soil C emissions for subsequent years. The stochastic weather generator (WxGEN; Nicks and Richardson, 1990) was used to produce future climate data: using the WMO 25-year historic daily records, including means and distribution characteristics of temperature and precipitation, WxGEN generated daily weather data beyond 2016 for each location. The calibration and sensitivity analyses of EPIC was conducted using long-term field data collected at fields in Texas, and reported by Izaurralde et al. (2001).

The EPIC model was employed to simulate soil management scenarios to determine the soil C sequestration for two built-in sample fields—with conventional tillage and fertilizer management—that have similar characteristics to the clay loam (CL) and sandy loam (SL) soils used in this project. Changes in the simulated field parameters of bulk densities, k_{sat}, FC, and AWC were adjusted based on the finding of this research project to simulate the influence of WBC amendment. These scenarios were based on percentage changes in the hydraulic characteristics and bulk density of the soil induced if WBC is incorporated in the soils.

Two soils were selected from the model in Dallas, TX, USA namely; clay loam SEAGOVILLE (59) (C): 0–1% and sandy loam AXTELL (13) (FSL): 1–5%. The CL and SL soil sample fields chosen for simulation have 27% silt and 22% sand, and 20% silt and 67% sand, respectively, pH values of 7.6 and 5.8, respectively, and OM contents of 3.9 and 2.9%, respectively. The mean crop yield reported (1999–2015) for corn and alfalfa are 5.1 and 6.4 t/ha, respectively, for the CL field and 3.2 and 4.7 t/ha, respectively, for the SL field.

The EPIC model was utilized because it seemed less complicated than other methods. The other reason was that it could determine the erosion of agricultural soils due to infiltration.

Results and Discussion

Soil bulk density

The soil ρ_{max} increased with compaction in all the treatments (Table VII.1) due to the decrease in the soil pore spaces and the rearrangement of soil particles in the soil matrix. Amendment with 10% PS_1 decreased the ρ_{max} of SL and CL soils compacted with 5 (5B) and 15 (15B) rammer blows (Table VII.1). When SL (SL-5B; ρ_{max} =1.28±0.02 t/m^3) soil was amended with either 10% $PS_{1,2}$ or 10% PS_3, they both resulted in the same decrease in the soil ρ_{max} (i.e., the SL-$PS_{1,2}$-10%-5B; ρ_{max} = 1.16±0.01 and SL-PS_3-10%-5B; ρ_{max} = 1.17±0.01 t/m^3). In contrast, when CL (CL-5B; ρ_{max} =1.24±0.02 t/m^3) soil was amended with either 10% $PS_{1,2}$ or 10% PS_3, they both resulted in a different decrease in ρ_{max} (*i.e.*, the CL-$PS_{1,2}$-10%-5B; ρ_{max} = 1.02±0.03 and CL-PS_3-10%-5B; ρ_{max} = 1.07±0.01 t/m^3).

Table VII.1: Mean ± standard deviation of sandy loam (SL) and clay loam (CL) dry bulk densities after compaction with 5 or 15 rammer blows and before and after amendment with wood-derived biochar (WBC) with particle sizes of 0.5–420 and 420-841µm

Soil	**No. rammer blows**	**Dry bulk density (g/cm^3)**		
		0% WBC	**10% $PS_{1,2}$**	**10% PS_3**
SL	5	1.28±0.02a(a)	1.16±0.01b(a)	1.17±0.01b(a)
	15	1.53±0.02a(b)	1.32±0.03b(b)	1.34±0.03b(b)
CL	5	1.24±0.02a(a)	1.02±0.03b(a)	1.07±0.01c(a)
	15	1.48±0.02a(b)	1.24±0.01b(b)	1.38±0.01c(b)

Numbers followed by the same letter implies no difference in the same row, whereas numbers followed by same letters with parentheses implies differences in the same column.

Soil hydrological constants

The soil with a relatively high percentage of clay retained more moisture (higher AWC) than the soil with a relatively low clay content. The increase in compaction effort decreased the moisture content at saturation for both soils but did not change the AWC of the CL-5B soil as the FC and AWC did not change. By comparison, the AWC of the SL-5B soil increased due to the increase in the FC (Table VII.2). Ohu (1985) also concluded that as the compaction level increases, the AWC increases in the SL because water at FC is held more tightly at a higher soil ρ. The reason for the no changes in the FC even thought the θ_{sat} decreased for the CL-5B vs CL-15B soil is that the compaction efforts decreased the pores more in proportion to the FC pores.

WBC increased the SL-5B soil water retention at FC, regardless of the WBC particle size (Table VII.3). The application of $PS_{1,2}$ at 10% did not change the FC and AWC values of the CL soil. The PWP did not differ for either soil type after amendment with either particle size of WBC at any compaction level (Table VII.3). Similar results were found in several other studies, where no improvement in terms of water retention at PWP, despite the addition of biochars with a high proportion of micropores (Andrenelli et al. 2016; Downie et al. 2009; Eastman 2011; Hardie et al. 2014; Laird et al. 2010; Major et al. 2009). These results confirm that the main purpose of biochar addition to soils is to influence the soil structural characteristics of pores >0.2 μm.

With regards to the θ_{sat} values, only the CL-5B soils amended with the finer WBC at 6 and 10% were higher than the control. This could be attributed to the ability of the finer WBC amended CL-5B soil to absorb more moisture at high dosages. However, under suction pressure the water is released faster because of the pore water held by the WBC-amended CL soil therefore the FC did not show any difference.

The FC of amended SL-5B soil increased with compaction (Table VII.2). The addition of WBC to the soils increased the amount of water absorbed due to the creation of pores (Table VII.3). However, at the highest compaction effort of 15B, the influence of the WBC diminished.

Table VII.2: Statistics related to the (%) volumetric water content at saturation, FC, PWP and AWC of the SL and the CL soils with different rammers blows

Soil	v_{sat}(%)	FC (%)	PWP (%)	AWC (%)
SL-5B	32.3±0.6(a)	15.8±1.0(a)	9.3±0.8(a)	6.5±1.7(a)
SL-15B	29.5±0.9(b)	17.9±0.9(b)	9.3±0.8(a)	8.6±1.7(b)
CL-5B	48.0±1.3(a)	37.3±1.1(a)	21.0±1.3(a)	16.3±2.3(a)
CL-15B	43.0±1.0(b)	38.7±1.8(a)	20.4±1.2(a)	18.3±2.9(a)

Numbers followed by the same letter in parenthesis implies no difference in the same column

Table VII.3: Statistics related to the volumetric water content at saturation FC, PWP and AWC of the SL and the CL soils with different WBC particle sizes

Soil	v_{sat}(%)	FC (%)	PWP (%)	AWC (%)
SL-5B	32.3±0.6(a)	15.8±1.0(a)	9.3±0.8(a)	6.5±1.7(a)
SL-$PS_{1,2}$-10%-5B	37.8±0.9(b)	24.0±1.1(b)	9.7±0.9(a)	14.3±2.0(b)
SL-PS_3-10%-5B	34.9±2.0(c)	19.0±1.0(c)	9.8±0.8(a)	9.2±1.7(c)
CL-5B	48.1±1.3(a)	37.3±2.1(a)	21±1.3(a)	16.3±2.3(a)
CL-$PS_{1,2}$-10%-5B	52.6±2.3(b)	39.3±3.2(a)	22.5±1.3(a)	16.8±2.3(a)
CL-PS_3-10%-5B	48.9±1.6(a)	36.4±3.9(a)	20.8±2.0(a)	15.6±2.7(a)

Numbers followed by the same letter in parenthesis implies no difference in the same column.

Soil k_{sat}

The SL-5B and CL-5B soils had a k_{sat} of 6.8±1.0 and 0.25±0.05 mm/h, respectively. The soil k_{sat} decreased with increasing percentage of fine soil particles in the soil matrix due to the presence of relatively small pores (Figures VII.1 and VII.2). These small pores hinder soil water movement, thus decreasing the soils k_{sat} (Ohu 1985).

Increasing the compaction effort decreased the k_{sat} of the SL soil from 6.8±1.0 to 0.35±0.2 mm/h (Figure VII.1) and of the CL soil from 0.25±0.05 to 0.09±0.02 mm/h (Figure VII.2). This reduction was due to the decline in the size of large pores with compaction, which consequently decreased the flow of water in the soils. Therefore, it is evident from the SWRC analysis -next section- that both the FS and TP volume decreased in the soils when the compaction effort increased. Ohu et al. (1985) found that the k_{sat} of a SL and CL soils decreased when the compaction level increased. The k_{sat} of the SL-5B soil decreased with increasing dosage of $PS_{1,2}$ (Figure VII.1) due to the decrease in the soil pore geometry; reduction in pore spaces reduces the movement of water through the soil. The drop in k_{sat} values was higher at 0.5–3% WBC dosages than at 6–10% dosages (Figure VII.1), probably because the finer WBC particles occupied the voids of the soil at lower dosages.

The CL-5B soil k_{sat} increased when amended with 6 and 10% $PS_{1,2}$ (Figure VII.2) because of the significant increase in both the FS and TP -next section analysis. WBC amendment did not affect more compacted CL soils (CL-10 and CL-15B). Asai et al. (2009) also found that clay soil with 48% clay and 18% sand had an increase in the k_{sat} when WBC was amended at 16 t/ha.

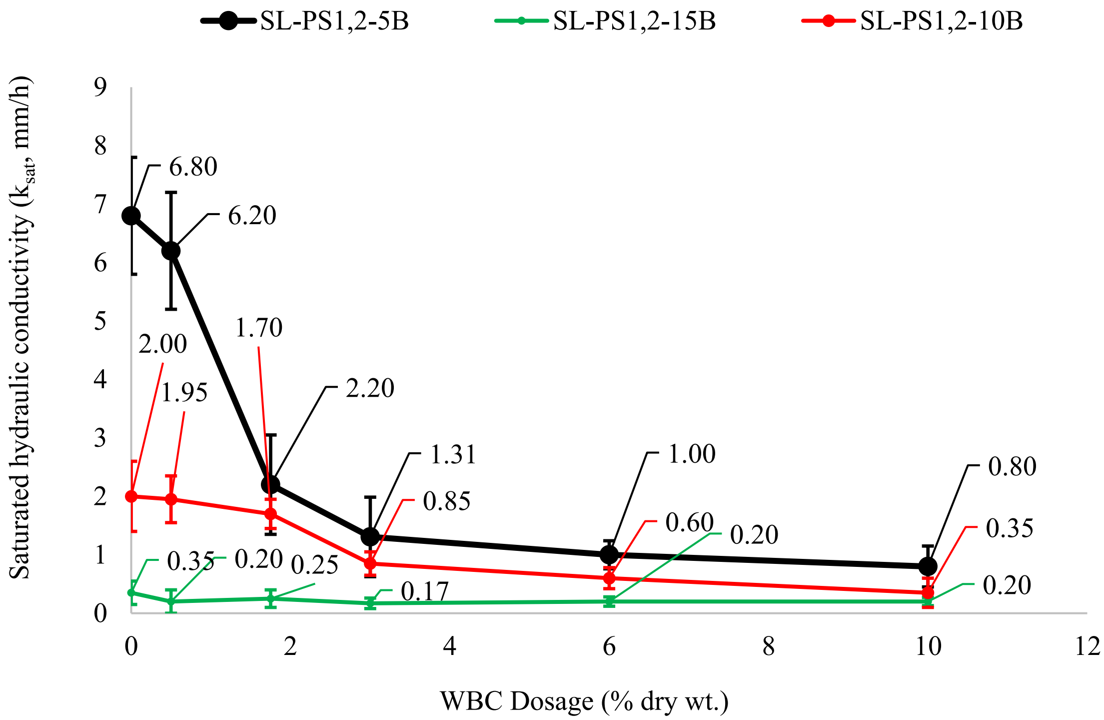

Figure VII.1: Saturated hydraulic conductivity of sandy loam (SL) soil amended with wood-derived biochar with a particle size of 0.5–425 µm and subjected to 5, 10 or 15 rammer blows

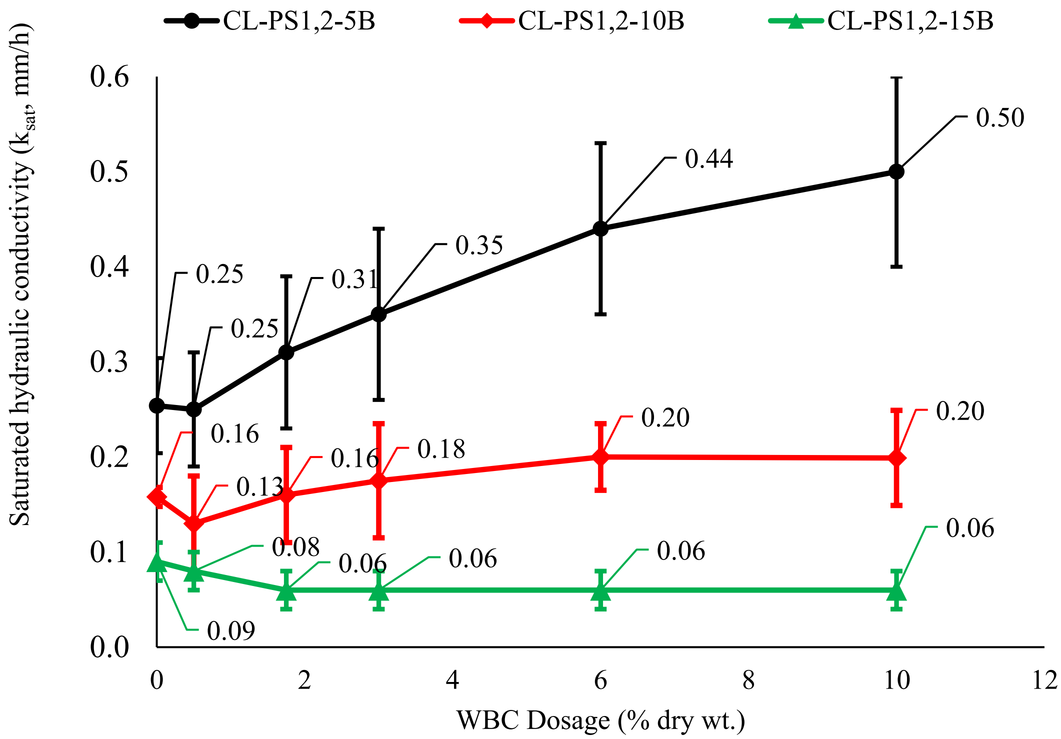

Figure VII.2: Saturated hydraulic conductivity of clay loam (CL) soil amended with wood-derived biochar with a particle size of 0.5–425 µm and subjected to 5, 10 or 15 rammer blows

The magnitude of the reduction in the k_{sat} of the unamended CL soil due to compaction increased with $PS_{1,2}$ dosage, whereas the SL soil showed the opposite trend (Figures VII.1 and VII.4). The k_{sat} of the CL (CL-5B *vs* CL-15B) soil decreased 64%, while the k_{sat} of the CL soil amended with 10% $PS_{1,2}$ decreased 98% when compaction effort was increased from 5B to 15B. By comparison, the k_{sat} of the SL (SL-5B *vs* SL-15B) soil decreased 95%, while the k_{sat} of the SL soil amended with 10% WBC PS_1 decreased 75% when compaction effort was increased from 5B to 15B. As the compaction effort increased, both the FS and the TP decreased in the SL and the CL soils -as described in the next section. On the other hand, the WBC decreased both the FS and the TP of the SL soil. Therefore, at higher compaction levels, the effect of the WBC on decreasing the FS and TP were dampened because of the influence of the compaction efforts on decreasing the larger soil pores.

The relative reduction in the k_{sat} of the SL soil could also be due to the resistance to compaction induced by the presence of WBC particles in the soil matrix, which could be due to the rearrangement of the soil particles rather than decreasing the pore volume at higher compaction efforts and could account for the lack of response of k_{sat} at higher compaction levels. In other words, the SL soil particle arrangement due to compaction created fewer pores when amended with $PS_{1,2}$, resulting in soils at higher compaction efforts having a less significant decrease in the pore volume compared to unamended soils.

Amendment with the coarser WBC did not show the same increase in the k_{sat} of the CL-5B soil at any amendment levels (Figure VII.3). However, the SL-5B soil k_{sat} decreased at dosages of PS_3-6% and PS_3-10%. At high compaction efforts of 10B and 15B, the k_{sat} did not differ for any soil type with changing particle sizes $PS_{1,2}$ or PS_3. Increasing the rate of application to 10% may not significantly affect the k_{sat} of the SL-5B soil, since the curve appears to plateau.

Soil pore size distribution

The measured saturated volumetric moisture content (v_{sat}) and hydraulic parameters (v_r, α^{-1}, and n) estimated by the RETC software are shown in Table VII.4. Low root mean square error (RMSE) values were obtained for all treatments, which confirms the reliability of the adopted model. The values of the model parameters differed between treatments in the α^{-1} but not in the n parameter, which differentiated the amended soils from the control. With higher α^{-1} value, a wider capillary saturation zone is evident in the amended soils. The α^{-1} values increased primarily due to the increase in air entry pressure when soils are more compacted. The n represents the slope of the curve, which increases as the soil texture becomes coarser. The n was not different, which means soil did not change in texture upon amendment. Water content within the RPs (θ_r) estimated by the RETC did not change in all treatments, because at high h, soil texture mainly controls soil hydrologic behavior, regardless of the WBC particle size or dosage.

Results from the soil pore size distribution analysis (Table VII.5) show that when the soils were more compacted, there was a decrease in the FS and TP volumes and a decrease in the SP of the CL soil. The SP of the SL soil did not change. The compaction did not affect the RP of the SL or CL soils. It could be deduced that the FS and TP volume of the SL and CL soils decreased due to compaction (Table VII.5). This led to lower k_{sat} and higher FC for compacted SL soil. It can be inferred from Table VII.5 that the total pore volume decreased when the CL and the SL soil compaction effort increased from 5B to 15B. The major influence of compaction was on the FS and TP pores more than the SP pores.

Table VII.4: Statistics related to the optimized values of residual water content (v_r) and van Genuchten shape parameters (α^{-1}, n and m) for the soil treatments in this study at 5B. Measured saturated water content (v_s) is indicated. Within each column different letters designate significant differences (*p < 0.05*) between treatments. Standard deviation is reported, RMSE of the residual with respect to the measured water content values is also displayed

Treatments	Measured v_{sat} (cm^3/cm^3)	Estimated parameters by RETC code				RMSE $*e^{-4}$ (cm^3/cm^3)
		v_r (cm^3/cm^3)	α^{-1} (kPa)	n	$m = 1 - n^{-1}$	
SL-5B	0.32±0.6(a)	0.09±0.022(a)	6.7±3.4(a)	1.83±0.04(a)	0.45±0.02(a)	1.7
SL-$PS_{1,2}$-10%-5B	0.38±0.9(b)	0.09±0.054(a)	15.4±4.8(b)	1.89±0.07(a)	0.47±0.04(a)	1
SL-PS_3-10 %-5B	0.35±2(c)	0.09±0.033(a)	10.0±6.5(a)	1.81±0.09(a)	0.45±0.03(a)	3.3
CL-5B	0.48±0.15(a)	0.18±0.01(a)	15.4±2.01(a)	1.5±0.04(a)	0.33±0.2(b)	0.8
CL-$PS_{1,2}$- 10%-5B	0.53±0.22(b)	0.17±0.01(a)	14.2±3.4(a)	1.5±0.7(a)	0.33±0.2(b)	0.4
CL-PS_3-10%-5B	0.49±0.07(a)	0.19±0.01(a)	14.2±6.6(a)	1.6±0.03(a)	0.38±0.022(b)	0.6

Table VII.5: Statistics of volumetric water content (%) related to different sizes of pores for the SL and CL soils compacted with various rammers blows. Within each column, different letters indicate significant difference between the treatments. Standard deviation is reported

Treatments	Fissures & TP >50 µm	SP 50 – 0.5 µm	RP <0.5 µm	Whole pore sizes range
SL-5B	5.4±0.6(a)	17.3±2.4(a)	9.6±3.0(a)	32.3±1.1(a)
SL-15B	2.0±0.4(b)	17.7±1.4(a)	9.8±1.7(a)	29.4±0.9(b)
CL-5B	2.0±0.9(a)	23.1±1.2(a)	22.8±1.2(a)	47.9±2.1(a)
CL-15B	0.4±0.1(b)	20.3±1.7(b)	22.3±1.7(a)	43±1.2(b)

Results are in % of total volume of soil

Table VII.6: Statistics of volumetric water content (%) related to different sizes of pores and the treatments of the soils compacted with five rammer blows (5B). Within each column, different letters indicate significant difference between treatments. Standard deviation is reported

Treatments	FS&TP > 50 µm	SP 50 – 0.5 µm	RP < 0.5 µm	Whole pore sizes range
SL-5B	5.4±0.6(a)	17.3±2.4(a)	9.6±3.0(a)	32.4±1.1(a)
SL-$PS_{1,2}$-10%-5B	2±0.3(b)	25.2±2.0(b)	10.6±3.0(a)	37.8±1.2(b)
SL-PS_3-10 %-5B	3.4±0.7(c)	21.2±2.3(c)	10.3±2.8(a)	34.9±2.2(c)
CL-5B	2.0±0.4(a)	23.1±1.1(a)	22.8±2.0(a)	47.9±2.3(a)
CL-$PS_{1,2}$-10%-5B	2.6±0.3(b)	27.4±1.0(b)	22.5±2.2(a)	52.6±2.3(b)
CL-PS_3-10%-5B	2.3±0.4(ab)	24.4±0.9(a)	22.2±0.8(a)	48.9±1.8(a)

Results are in % of total volume of soil

The total pore volume increased when either fine or coarse WBC particles were amended to the SL-5B soil at 10% (Table VII.6). The total water stored in the SL-5B soil pores amended with PS_3 declined 7.7% over the SL-5B amended with $PS_{1,2}$ treatment. This decline is due to the relatively large decrease in the FS and TP. The amendment increased the porosity of the SP in the SL soil, resulting in more water held at FC. Thus, the new pores created in the SL soil due to WBC incorporation were between 50 and 0.5 μm but decreased in the pore ranges >50 μm. The statistical analysis in Table VII.6 showed that the $PS_{1,2}$ addition to the CL-5B soil increased the total pore volume of the treated soil over the control, in the pore size range >0.5 μm, whereas, the water content in the residual pores was similar in all the treatments of the CL-5B soil. This increase in the total pore volume is due to an increase in the FS, TP and SP of the CL-5B.

The volume of pores within the FS and TP class increased up to 30% over the control when $PS_{1,2}$-10% was applied to the CL soil. The analysis of the SWRCs illustrated that the volume of SP in the amended soils increased after amendment with $PS_{1,2}$. This increase in water content in the SP could be attributed to the WBC contribution to increased porosity in the soil. The improvement in the water retention values of the CL amended soil was due to the increase in the microporosity of the soils. Nevertheless, the high variability that affects the sizes class of fissures (pore sizes>500 μm) could be responsible for the lack of significance in CL-5B (Table VII.6). As the WBC particle sizes increased, the effect on soil pore structure was not sustained under higher compaction efforts of 10B and 15B.

The particle sizes of the WBC incorporated into the soil matrix influenced the volume of the soil pores differently. This variation could be attributed to the effect of the particle sizes such that they either occupy soil pores or take the place of soil particles. In addition, WBC particles are more hydrophobic than soil particles. When subjected to tension, more water would be released, especially at low suction, because the WBC lowers the force of adhesion of soil particles to water.

Soil unsaturated hydraulic conductivity (k_{unsat})

The statistical analyses of the soils k_{unsat} determined by Eq VII.5 of selected treatments are presented in Tables VII.7 and VII.8.

Table VII.7: Unsaturated hydraulic conductivity of selected unamended treatments

Treatments	K_r	k_{unsat} (mm/h)
SL-5B	0.06	0.41±0.15(a)
SL-15B	0.17	0.06±0.01(b)
CL-5B	0.25	0.06±0.01(a)
CL-15B	0.35	0.03±0.01(b)

Numbers followed by same letters with parentheses implies differences in the same column

Table VII.8: Unsaturated hydraulic conductivity of selected treatments at 5B

Treatments	K_r	k_{unsat} (mm/h)
SL-5B	0.06	0.40±0.09(a)
SL-$PS_{1,2}$-10%-5B	0.17	0.13±0.08(b)
SL-PS_3-10%-5B	0.10	0.29±0.09(c)
CL-5B	0.25	0.06±0.01(a)
CL-$PS_{1,2}$-10%-5B	0.25	0.13±0.01(b)
CL-PS_3-10%-5B	0.21	0.07±0.01(a)

Numbers followed by same letters with parentheses implies differences in the same column

Table VII.7 shows that as compaction increased, the k_{unsat} of the SL soil decreased. On the other hand, there was no difference in applying $PS_{1,2}$-10% to the CL-5B soil k_r (Table VII.8). Therefore, it might be advisable to apply WBC with smaller particle sizes range than (0.5–425 µm) to induce changes in the CL soil infiltration rates.

Simulated carbon sequestration

It should be noted that one kg of WBC contains 0.2 kg of organic C (flexible pool) and 0.7 kg of aromatic C (fixed pool). The amount of WBC applied at a dosage of 10% to a depth of 0.3 m to a field having a ρ of 1,350 kg/m^3 is determined to be 375 t/ha. If the WBC has 20% aromatic C, the amount of C sequestered in the soil (negative emission) at a dosage of 10% WBC is 20 tC_{fixed}/ha. The first application of WBC itself accounts for 20 t/ha of C_{fixed}. This is a one-time C budget of

C$1,000/ha (Eastman 2011). This can be considered the baseline for carbon C sequestration credits, which may help fund any additional WBC treatment of the field.

The EPIC model output did show significant differences in C mineralization between the management scenarios. The unamended SL and CL soils has total C emissions of 0.532±0.07 tC/ha/y and 0.720±0.02 tC/ha/y, respectively. The SL and CL soils amended with $PS_{1,2}$-10% released less C (0.071±0.003 tC/ha/y or 13.3% decrease in C emissions and 0.091±0.006 or 12% decrease in C emissions, respectively). This decrease in C emissions is due to the changes in the amended soils hydraulic properties and bulk density induced by $PS_{1,2}$-10% application. The C sequestration rate reported here is approximately double that estimated by Woolf et al. (2010) for biochar amendment to soils. These C gain can be considered the baseline for C sequestration credits, which may help fund any additional WBC to the field. Therefore, this assessment could assist farmers in adopting WBC to offset their C foot print.

Conclusions

1. This project analysis has evidenced that the SWRCs could be utilized to predict the influence of the WBC on the pore structure and the consequence on soil water flow.
2. The SWRCs illustrated a considerable decrease of pore volumes of the FS and TP for the amended SL soil. The particle sizes of WBC incorporated in the soil matrix seemed to influence contribution to soil water retention and hydraulic conductivity, even though WBC was less hydrophilic than soil particles.
3. The application of $PS_{1,2}$ WBC succeeded in improving the soil water retention properties, despite the short period (<24h) between the amendment of WBC and the soil sampling.
4. The addition of WBC to the soils increased pore spaces. Hence the soil may become more susceptible to compaction. However, the increase in the pore spaces will increase the

amount of water released to plants. In contrast, the AWC of the soils was found to decrease with an increase in the level of compaction from 5B to 15B.

5. Due to increased compaction from 5B to 15B, the unamended SL soil resulted in a relative decrease in the FS and TP of 63% (from 5.4% to 2% Table VII.5). This decreased the SL soil resulted in a decrease in the soil ksat of 96% (from 6.8 to 0.35 mm/h, Figure VII.1). The 10%-PS1,2 amendment to the SL soil decreased TP and FS by 63% (from 5.4 to 2% Table VII.6) which resulted in a decrease in the ksat of 88% (from 6.8 to 0.80 mm/h Figure VII.1). The SL soil FS and TP decreased by the same value (63%) due to either increased compaction from 5B to 15B or incorporation of $PS_{1,2}$-10%. However, the decrease in the ksat of the SL soil was more due to compaction than due to incorporation of $PS_{1,2}$-10% (96 vs 88%), which clearly indicates that WBC-amended SL soil has less resistance to water flow than non-amended soil. Although WBC increases the FS and TP of SL soil, it is not an indication of the actual sizes of the pore induced by the treatment, but rather of the volume of water held at a section level: water is not held very tightly with WBC amended soils due to the hydrophobicity of the WBC. Therefore, values in Table VII-6 for SL-WBC could be considered equivalent to a soil having these pore sizes and not the actual pore sizes in the amended soil-WBC mixture.

Connecting Text

In Chapter VII, WBC particle size affected how CL and SL soils responded to the amendment. **In Chapter VIII,** the same treatments are applied and the strength of the soils along the compaction curve and the tillage requirements are investigated for the same WBC particle sizes and amendment rate as in **Chapter VII**.

Chapter VIII

Influence of wood-derived biochar on the strength of agricultural soils and its implications on tillage requirements

Abstract

Farm equipment compacts agricultural soils. The degree of compaction-induced damage could be minimized if the behavior of the soil is understood. Therefore, the goals of this study were to experimentally investigate the influence of wood-derived biochar (WBC) amendment on strength parameters of sand loam (SL) and clay loam (CL) soils upon compaction and to theoretically investigate how WBC treatment affects the draft force and thrust of tractors on the soils. Existing soil failure models were employed to determine tillage power requirements relative to changes in soil shear parameters. Results showed that soil texture affected how WBC amendment influenced soil strength parameters. Further, 10% amendment of WBC with particle sizes of 0.5–420 μm ($PS_{1,2}$) to the CL soil decreased the tillage power requirements and increased soil area of disturbance but no changes in drawbar pull. By comparison, the SL soil amended $PS_{1,2}$-10% had a higher tillage power requirement, larger area of disturbance and higher drawbar pull. Moreover, the compaction state of soils amended with WBC could be predicted for given soil characteristics.

Keywords: Soil bulk density, soil penetration resistance, liquid limit, soil shear strength and wood-derived biochar

Introduction

Farm machinery applies external pressure to agricultural soils, which influences soil structure in different ways depending on the soil shear strength (τ), which in turn determines the required specifications and the performance of cultivation machines for improved agricultural production (Panwar and Siemens 1972; Raghavan et al 1979). Among methods to estimate soil τ, some directly measure τ (e.g., direct shear machine, grouser plate, translational shear box, shear graph, annular torsional shear apparatus, and shear vane; Johnson et al. 1987) and some predict τ based on observations of soil properties (Ohu et al. 1986). Raghavan et al. (1977) developed a linear regression to predict the τ of compacted clay soil from the soil consistency limits. This approach is advantageous because as moisture is added or removed from soils, deformations due to compaction can be predicted depending upon the state of the soil. Estimating the τ of soils in this way can account for the textural variability in soils reacting to applied loads.

Tillage tools apply forces on soils, resulting in soil failure; that is, the soil yields by shear, compression, tension, and plastic flow. The amount of energy required during a tillage operation depends on soil conditions, tillage tool geometry, and operating parameters (Ashrafi Zadeh 2006; McKyes 1985). The stress state that causes soil fracture or plastic flow is a measure of the soil τ. Thus, shear failure is a function of the stress state that causes failure. Soil shear parameters such as c and ϕ influence soil failure (Ohu, 1985). Soil τ are related to the upward confining pressure (Sprangler and Handy, 1982).

Applying biochar—biomass decomposed in the absence of oxygen at temperatures of 250–700°C (Yuan et al. 2014)—to soils could ameliorate soil failure behavior. Depending on the dosage, the magnitude of force required to shear the soil could be altered by the biochar particles in the soil matrix. Predicting the tillage tool draft and energy requirements after amendment is necessary to design tillage implements and optimize tillage operation management. For example, tool depth and width of cut, shape (including cutting edges), arrangement, and travel speed are factors that could affect draft and energy efficiency. Models of soil-tool interactions for different tool configurations and soil conditions (Ashrafi Zadeh 2006; Chi and Kushwaha 1991; Godwin and Spoor 1977; McKyes 1978; Reece 1965; Swick and Perumpral 1988) could be used to predict tool energy requirements for a soil-biochar mix. The Hettiaratchi and Reece (1967) and McKyes (1985) models are widely used to predict the soil failure.

Therefore, the primary objectives of this study were to quantify the effects of adding wood-derived biochar (WBC) of two particle size ranges and dosages on the post-compaction T and PR of two soils differing in texture, and to predict the PR of the compacted soil-WBC mixture from the soil consistency limits. The secondary objective was to theoretically investigate the power requirements for tillage of the soil-WBC mixture.

Methods

Soil unit weight and overburden pressure

The soil unit weight (γ, N/m^3) after each compaction effort is the wet weight per unit volume in the standard compaction mold. The soil over burden pressure (Q_p, kPa) is the wet unit weight of the soil multiplied by the depth of the soil column.

Static pressure equivalent to rammer blows

Raghavan and Ohu (1985) developed a linear regression equation describing the relationship between the static pressure equivalence (P_c in kPa) and the number of Proctor rammer blows ($Proc_b$) as follows:

$$P_c = 22.1 \times Proc_b + 66.7 \qquad \text{(Equation VIII.1)}$$

Predicting the PR of the soil-biochar mix

The Ohu (1985) model for predicting PR in agricultural soils amended with varying compositions of organic matter (OM) and compacted in a Proctor mold was examined for its suitability with the compacted soil-WBC mixture. This model was developed based on the dimensional analysis technique using the least squares regression analysis to obtain the best fit curve from measured laboratory data, resulting in Equation VIII.2.

$$PR/P_c = A_1 (\tau/Q_p)^{vn_1} \quad \text{(Equation VIII.2)}$$

Where, PR is the soil penetration resistance (kPa), v is soil volumetric moisture content (m^3/m^3), and A_1 and n_1 are constants depending upon the treatment. τ, A_1 and n_1 depend of the soil θ_{ll} according to Equations VIII.3, VIII.4 and VIII.5.

Ohu (1985) related the maximum shear along the compaction curve (τ_{max}) of soils to the P_c applied to compact the soils (Equation VIII.3).

$$\tau_{max} = a_o + r P_c \quad \text{(Equation VIII.3)}$$

Where, a_o is the value of τ_{max} of the soil at zero P_c and r is the rate of increase in τ_{max} with P_c. Each soil treatment has distinct a_o and r values. Since each soil treatment has also a distinct θ_{ll}, the a_o and r are correlated with the soil θ_{ll}. (the θ_{ll} laniary changed with the change in the amount of OM incorporated in their soils) the c_1-c_4 are constants related to the changes in the θ_{ll} and the values of the a_o and r.

$$a_o=c_1 \theta_{ll} +c_2 \quad \text{(Equation VIII.4)}$$

$$r =c_3 \theta_{ll} +c_4 \quad \text{(Equation VIII.5)}$$

Nicholas (1932) estimated the τ of soils along the compaction curve from soil θ_{pl}, *PI* and P_c. Ohu (1985) observed that the τ_{max} of soils with varying OM occurs at 55% of the soil θ_{ll}. Based on this observation, they modified the Nicholas (1932) model to estimate the τ at any point on the compaction curve of plastic and non-plastic soils (Equation VIII.6).

$$\tau = (\theta/0.55\theta_{ll})(a_o+(0.55\theta_{ll}\, r\, P_c/\theta)) \pm [(1-(\theta/0.55\theta_{ll}))\times(a_o+(\theta\, r\, P_c/0.55\theta_{ll})] \qquad \text{(Equation VIII.6)}$$

Where, θ is the gravimetric water content at which the τ is required (%). The negative and positive signs are for the rising and falling portions of the compaction curve, respectively. Therefore, from the soil θ_{ll}, θ, and P_c (i.e., farm machinery), the state of compaction of the soil (PR) could be predicted from Equations VIII.2 to VIII.6.

The applicability of the PR model (Equation VIII.2) of Ohu (1985) was tested by comparing model output to measured data (τ, P_c, θ_{ll}, τ_{max}, γ, Q_c, and PR) to determine the constants (a_o, r, c_1, c_2, c_3, c_4, A_1 and n_1) of the τ_{max} and PR models (Equation VIII.2 and VIII.6) for WBC amended soils. The reason for utilizing the Ohu (1985) model was that it is the only model available in the literature that could determine a soil PR from a simple test such as the θ_{ll}.

Determination of the power requirement of a tillage tool

Tables VIII.1 and VIII.2 show the equations, parameters, and variables used to theoretically determine the power requirements for a tillage tool (P_{req}), soil disturbance area (A_i), and draw bar pull (D_{pull}).

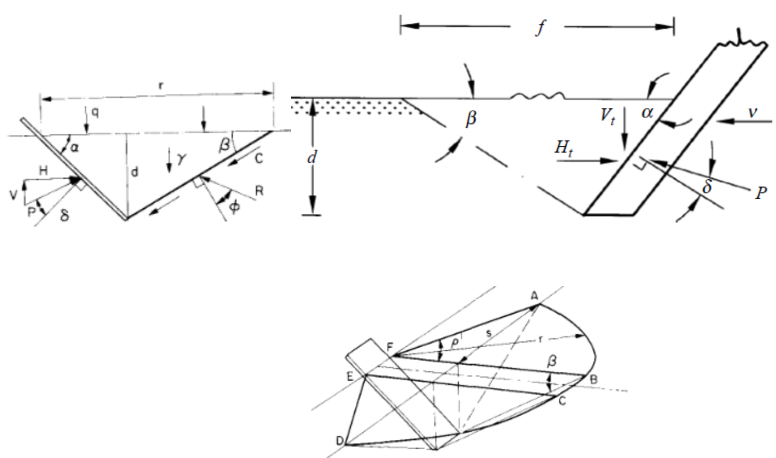

Figure VIII.1: Soil failure in front of a tillage tool from McKyes (1989)

Table VIII.1: Equations used to theoretically determine the tillage requirement, soil disturbed sectional area, and drawbar pull

Description	Number	Equation	Reference
Power required to pull a tillage tool (hp)	VIII.7	$P_{req} = 1.34 \times H \times V \times W_d$	Barger et al. 1952
Draft force (kN/m)	VIII.8	$H = F_f \sin(\alpha_c+\delta) + F_s \sin \alpha_c + c_a d_e \cos \alpha_c$	Godwin and Spoor 1977
Forward failure force (kN/m)	VIII.9	$F_f = \gamma d_e^2 N_\gamma + c d_e N_c + c_a d_e N_a$	Godwin and Spoor 1977
Sideways failure force (kN/m)	VIII.10	$F_s = (\gamma d_e^2 N_{s\gamma} + c d_e N_{sc})K_\alpha$	Godwin and spoor 1977
Effective wedge depth (m)	VIII.11	$d_e = d_t - ((K_\alpha \times W_i)/2)$	Hettiaratchi and Reece 1967
Width of implement (m)	VIII.12	$W_i = d_t / AR$	Hettiaratchi and Reece 1967
Width of soil disturbance (m)	VIII.13	$W_d = W_i + 2 S$	Hettiaratchi and Reece 1967
Critical rake angle (°)	VIII.14	$\alpha_c = 90^{\circ} - \delta$	McKyes 1989
Angle between soil surface and failure plan (°)	VIII.15	$\beta = Cot^{-1}\left(\frac{[sin(\alpha_c+\delta)\ sin(\delta+\Phi)/(sin\alpha_c\ sin\Phi)]^{1/2} - \cos(\alpha_c+\delta+\Phi)}{sin(\alpha_c+\delta+\Phi)}\right)$	McKyes 1989
The sectional area loosened by the tine (m^2)	VIII.16	$A_i = d_e^2 (Cot\beta + d_e W_i)$	McKyes 1989
Forward distance of soil failure	VIII.17	$r = 0.5 d_e^2(\cot \beta + \cot \alpha_c)$	Hettiaratchi and Reece 1967
The angle between tine face and failure plan (°)	VIII-18	$\rho' (m) = \cos^{-1}((d_e/r) \cot \alpha_c)$	McKeys 1989
Side crescent (m)	VIII.19	$S = r \sin \rho'$	McKeys 1989
Drawbar pull (kN)	VIII.20	$D_{pull} = T - MR$	ASAE standards D497
Tractor's thrust (kN)	VIII.21	$T = 0.75W [1-e^{-(0.3*(bD/W)*PR*s)}]$	ASAE standards D497
Motion resistance (kN)	VIII.22	$MR = W ((1.2/((bD/W) *PR)) + (0.04))$	ASAE standards D497

Table VIII.2: Parameters and variables used in equations of Table VIII.1

Variable and symbol	Unit	Value assumption	
Speed of deep tillage operation V	m/s	1	Barger et al. 1952
Soil unit weight γ	kN/m^3	Determined from standard Proctor mold after 5 blows	
Angle of soil metal friction δ	^{o}	0.66 of soil ϕ	Reece 1965
Soil metal adhesion c_a	kN/m^2	0.3 of the soil cohesion	Reece 1965
Tillage operational depth d_t	m	0.35 m for deep tillage	McKyes 1985
Reece Factor soil reaction component due to gravity N_γ	unitless	$N_{\gamma,\, c,\, a,\, sc\ or\ s\gamma}$ for a specific δ and ϕ $= N_{\delta=0} * (N_{\delta=\phi}/N_{\delta=0})^{\delta/\phi}$ where $N_{\delta=\phi}$ and $N_{\delta=0}$ are determined from plots depending on rake angle and ϕ. Hettiaratchi et al. (1966	
Reece Factor soil reaction component due to cohesion N_c	unitless		
Reece Factor soil reaction component due to adhesion N_a	unitless		
Reece Factor soil reaction component due to cohesional side failure N_{sc}	unitless		
Reece Factor soil reaction component due to gravitational side failure $N_{s\gamma}$	unitless		
Aspect ratio AR	unitless	5.5	Reece 1965
Inclination factor K_α	unitless	Determined from plot depending on the rake angle and soil angle of internal friction	
Soil cohesion *c*	kN/m^2	From shear vane method in the Standard Proctor mold mold after 5 blows	
Soil angle of internal friction ϕ	^{o}	Determined from direct shear box method	
Load on the tractors tires (W)	kN	10	
Slip coefficient (s)	unitless	0.15	ASAE standards D497
Soil PR	kPs	Determined in the Standard Proctor mold after 5 blows at PR_{max}	
Soil shear strength τ	kPa	Determined in the Standard Proctor mold after 5 blows at τ_{max}	
Tyre diameter D	m	2.2	

Results and Discussion

Soil overburden pressure and static pressure

The equivalent static pressures of the 5, 10, and 15 rammer blows are 175, 288, and 404 kPa, respectively. In unamended SL and CL soils compacted with 5 rammer blows (SL-5B and CL-5B), the Q_p increased with increasing soil θ (Figure VIII.2). For a given soil θ, the Q_p was higher for the SL than the CL soils. As compaction level increased in SL soil, the Q_p at a given soil θ increased (Figure VIII.3).

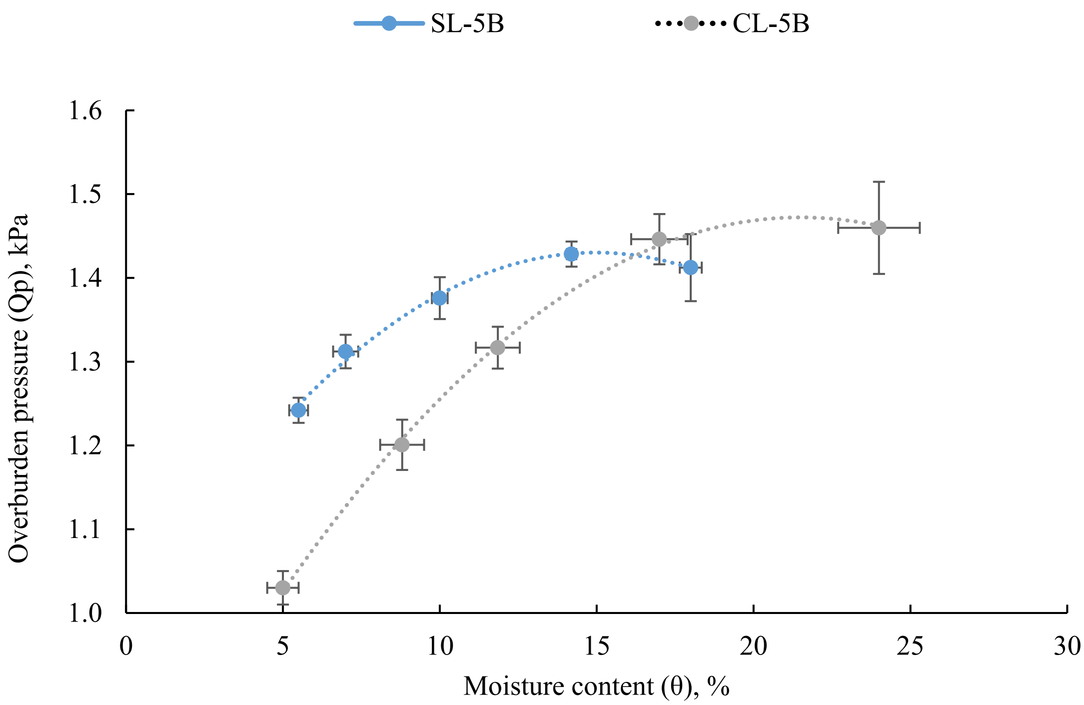

Figure VIII.2: Soil overburden pressure vs moisture content in unamended sandy loam (SL) and clay loam (CL) soils after 5 rammer blows (5B)

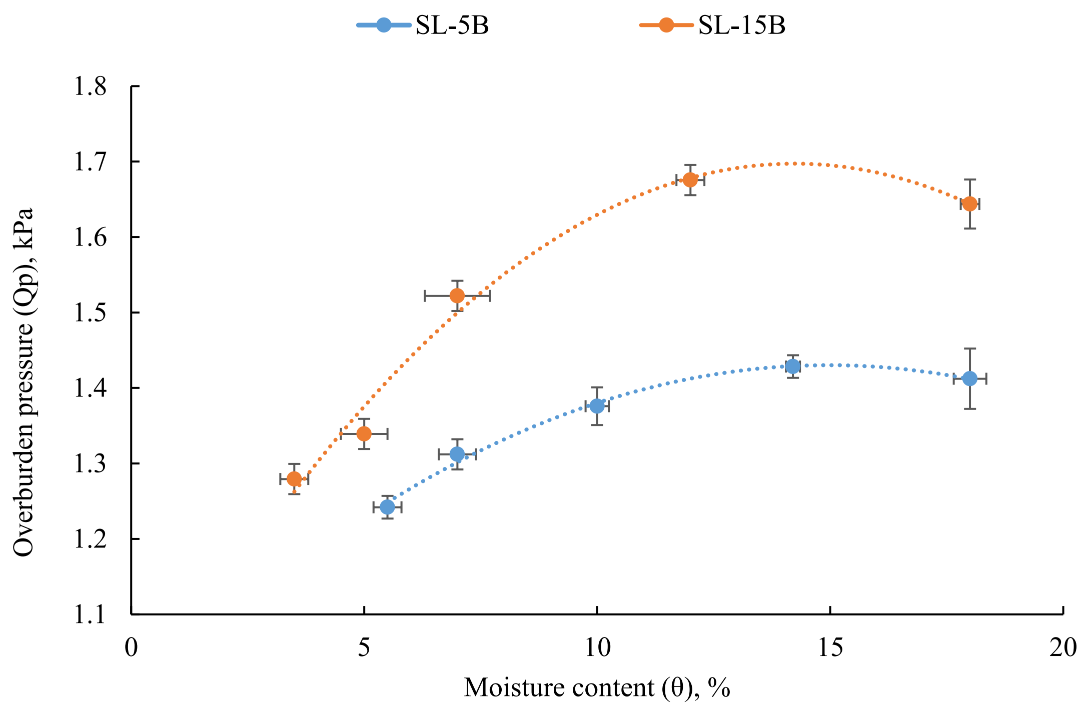

Figure VIII.3: Soil overburden pressure vs. moisture content of unamended sandy loam (SL) soil after 5, and 15 rammer blows of the Proctor compaction test

Amendment with the finer particle size WBC lowered the Q_p in SL (Figure VIII.5) and CL soils (Figure VIII.4 and VIII.5) at every soil θ, which is expected since Q_p is the product of the unit weight of the soil by the depth of the soil column, and WBC has a lower density (ρ) than soil.

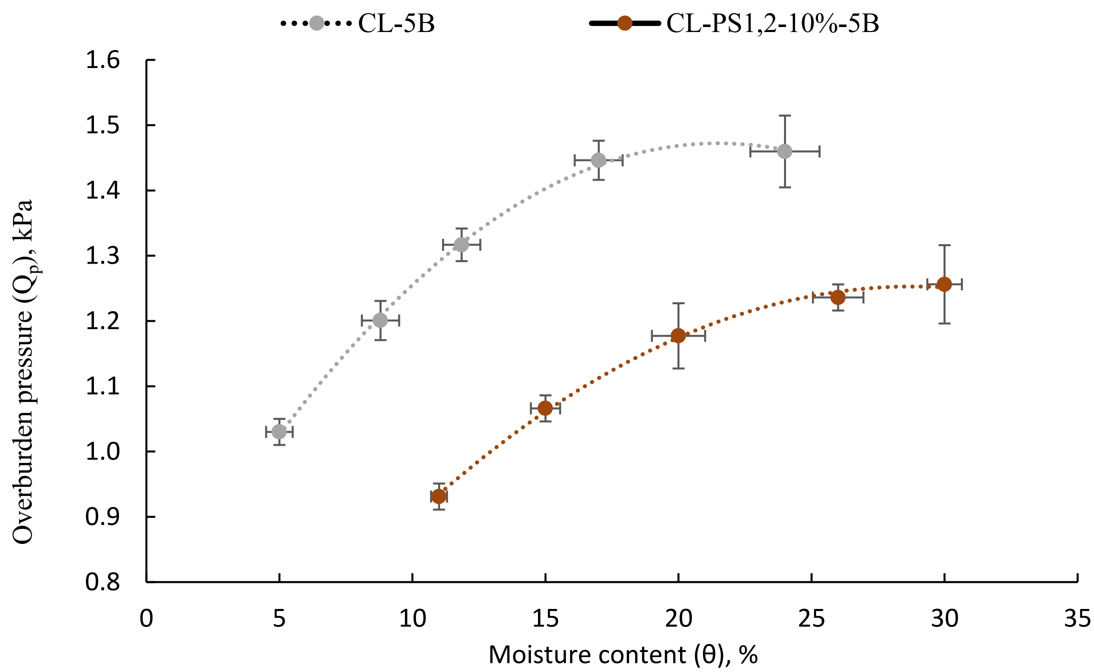

Figure VIII.4: Soil overburden pressure vs. moisture content of unamended (CL-5B) and amended (10% wood-derived biochar with a particle size of 0.5–425 μm [PS1,2]) clay loam soil (CL-5B-10%-$PS_{1,2}$) after 5 rammer blows

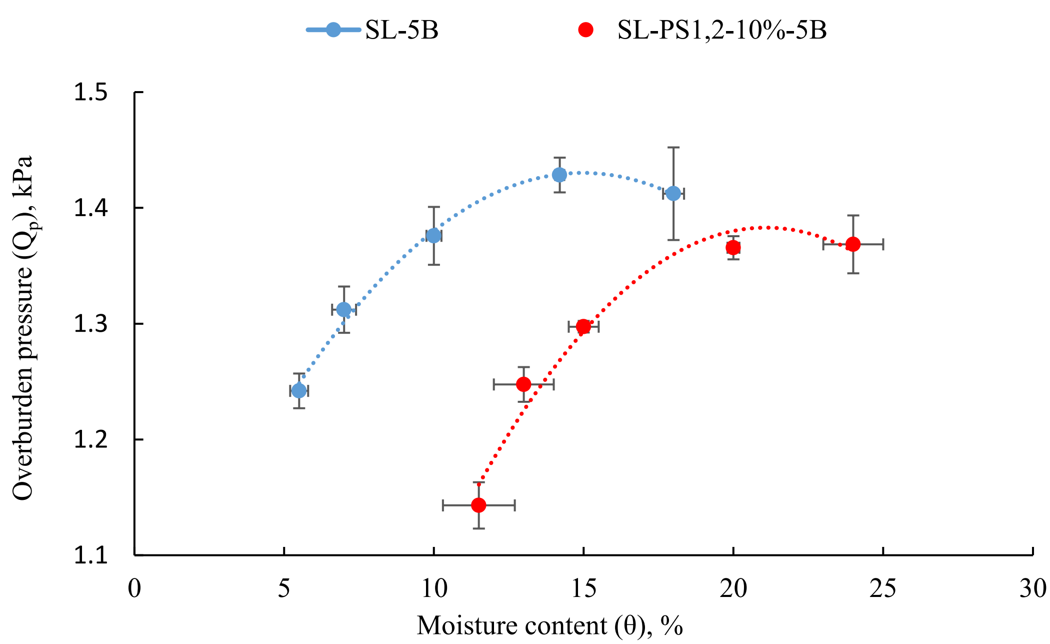

Figure VIII.5: Soil overburden pressure vs. moisture content of unamended (SL-5B) and amended (10% wood-derived biochar with a particle size of 0.5–425 μm [$PS_{1,2}$]) sandy loam soil (SL-5B-10%-$PS_{1,2}$) after 5 rammer blows during the Proctor compaction test

Soils PR and Ʈ along the compaction curve

For both soil types, the PR and Ʈ along the compaction curve increased with an increase in the soil θ to a maximum value (PR_{max} and Ʈ$_{max}$), then decreased with a further increase in θ (Figure VIII.6 and VIII.7). The soil PR and Ʈ along the compaction curve were lower in SL than CL compacted soils (Figure VIII.6). At low θ, soil c was low; it increased due to compaction with an increase in θ until high pore water pressure inhibited a further increase in c. Ohu et al. (1985) and Nicholas (1932) reported the same trend for the PR and Ʈ along the compaction curve.

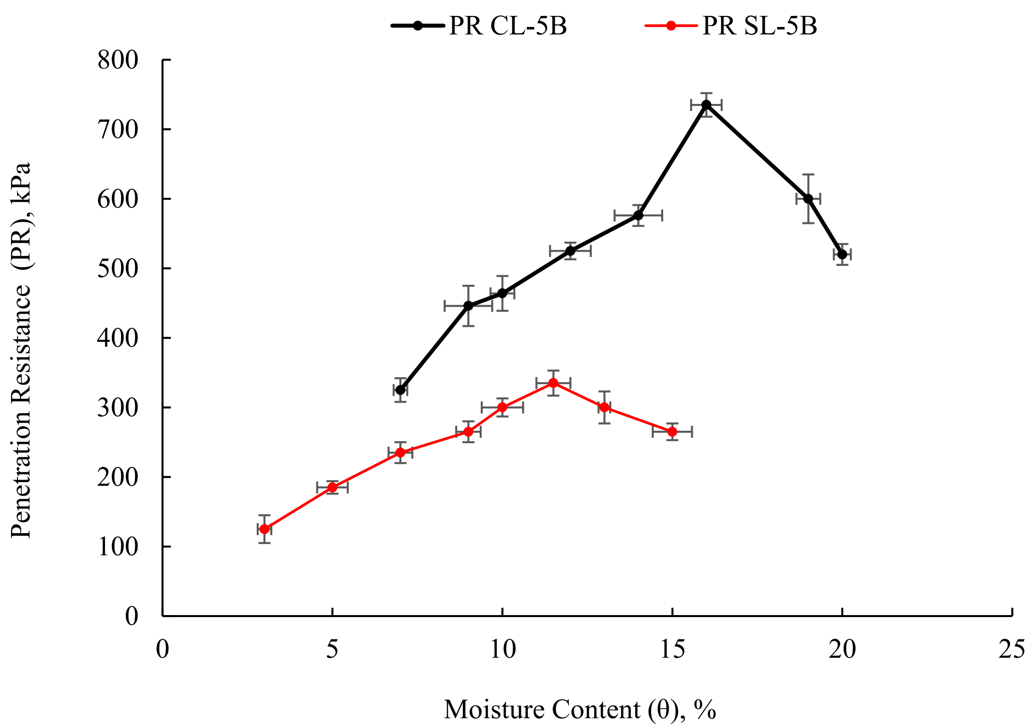

Figure VIII.6: Penetration resistance (PR) along the compaction curve of the clay loam soil

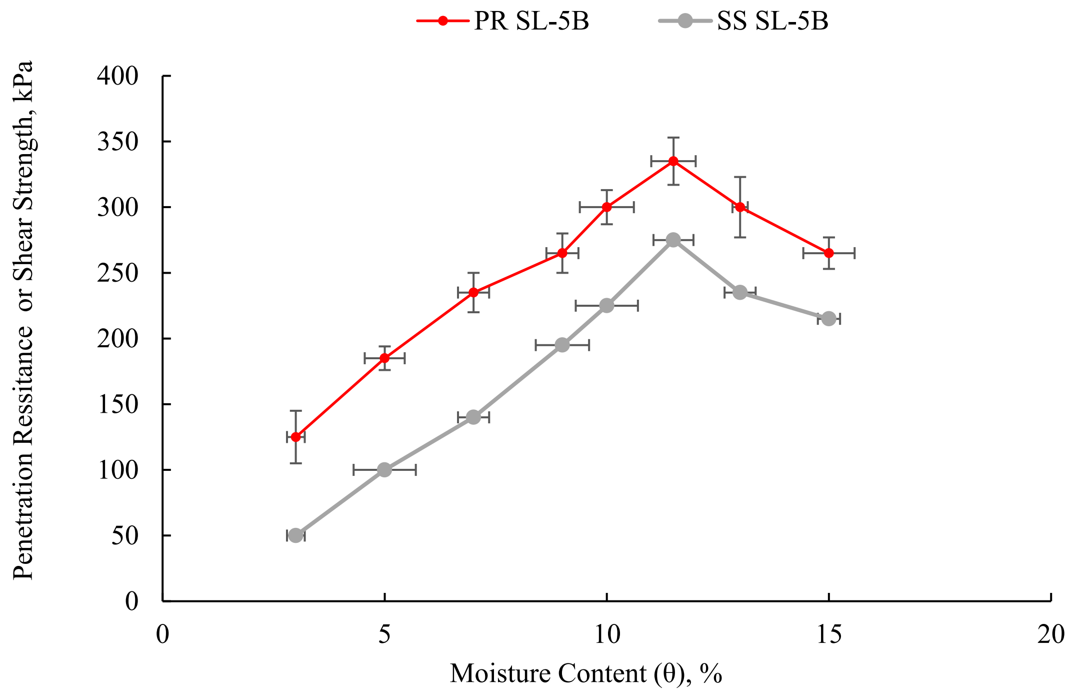

Figure VIII.7: Penetration resistance (PR) and soil shear strength (Ʈ) along the compaction curve of the sandy loam soil

Influence of compaction effort on soil PR and Ʈ along the compaction curve

More rammer blows resulted in an increase in the PR and Ʈ along the compaction curve of both CL and SL soils (Figure VIII.8). For example, an increase in the number of blows from 5 to 15 increased the PR_{max} of the CL soil by 67% and the SL soil by 124% (Table VIII.4). PR_{max} and $Ʈ_{max}$ occurred near the θ_{opt} of each treatment. These results agree with Ohu (1985) and Panwar and Siemens (1972). The PR_{max} and $Ʈ_{max}$ were 119 and 37% lower in SL than CL soils compacted with 5 rammer blows and 37 and 40% lower in SL than CL soils compacted with 15 rammer blows (Table VIII.3). The higher levels of compaction resulted in higher PR and Ʈ along the compaction curves because soils compacted with an elevated amount of forces have higher density, and therefore fewer pore spaces, which increases soil PR.

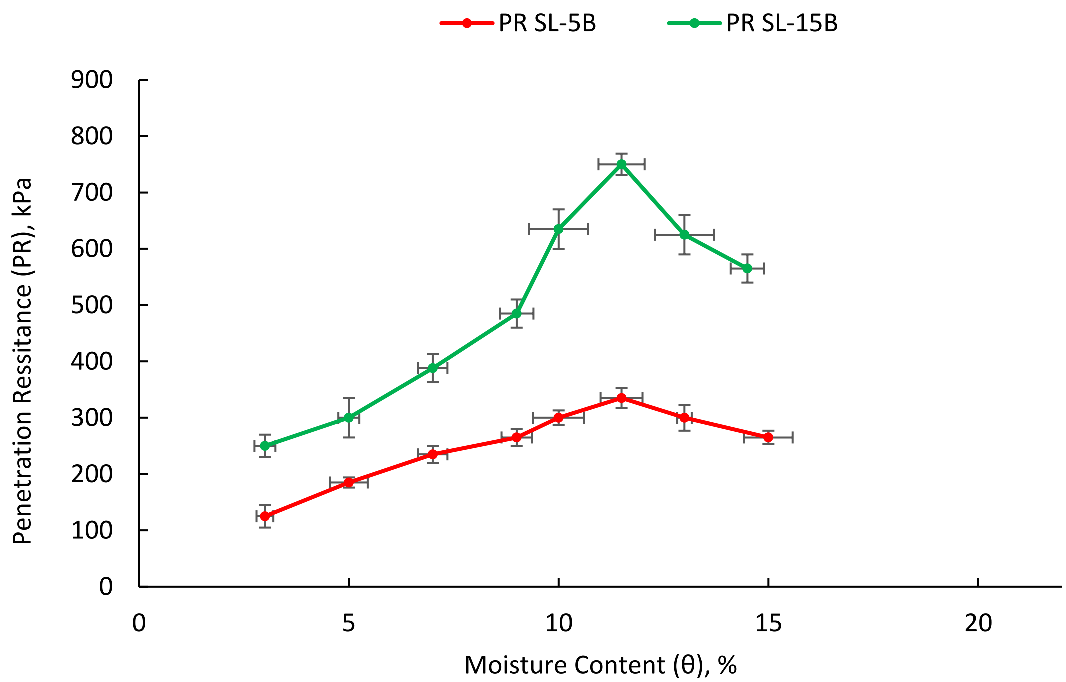

Figure VIII.8: Penetration resistance along the compaction curve of the sandy loam soil after 5 and 15 rammer blows

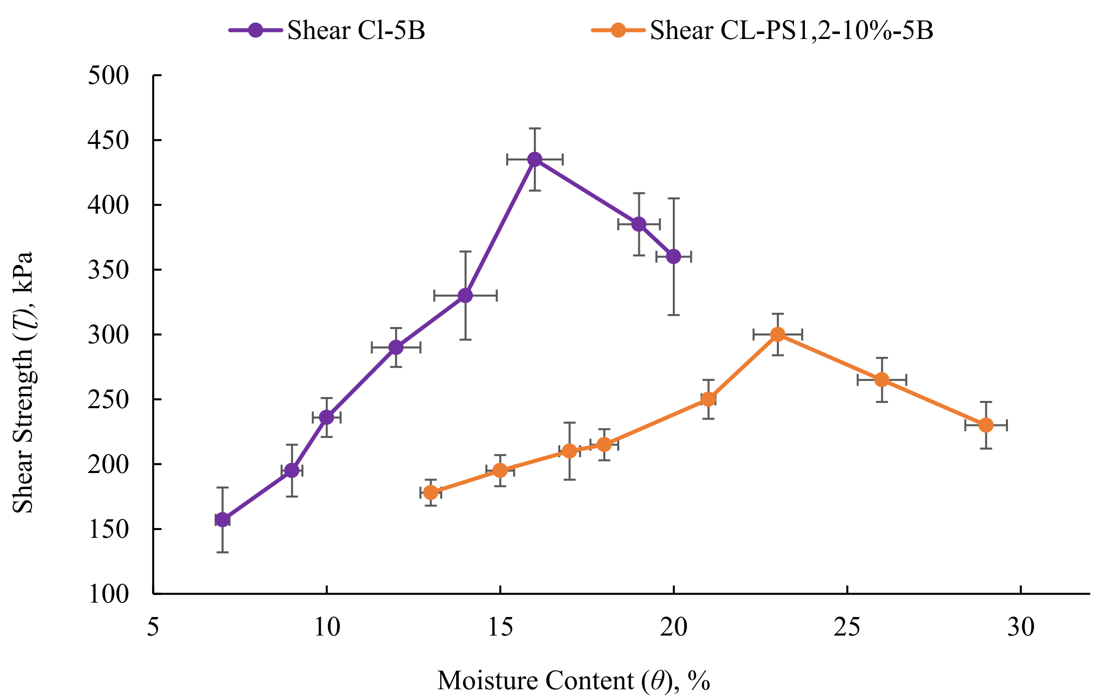

Figure VIII.9: Shear Strength along the compaction curve of the clay loam soil after 5 and 15 rammer blows

Table VIII.3: The PR_{max} and τ_{max} of sandy loam (SL) and clay loam (CL) soils with two compaction efforts

Soil	No. rammer blows	PR_{max} (kPa)	τ_{max} (kPa)	θ
SL	5	335±18	275±12	11.5±0.4
	15	750±19	455±18	11.3±0.5
CL	5	735±17	435±24	16.2±0.7
	15	1230±35	760±20	16.7±0.7

Influence of WBC on soil PR and τ along the compaction curve

The CL soil PR and τ along the compaction curve decreased when amended with 10% of the fine WBC (Figures VIII.10 and VIII.11), even at higher compaction levels. WBC amendment decreased the PR_{max} and τ_{max} of CL soil by 11.5 and 31%, respectively (Table VIII.4). This decrease was associated with higher θ, which likely produced a lubrication effect. This behavior of non-plastic soils has also been reported by Ohu et al. (1985) and Nichols (1932). In contrast, the SL soil PR_{max} and τ_{max} increased with the same amendment (Table VIII.4). The τ was higher in the $PS_{1,2}$ amended SL soil even though the moisture content was higher than the PS_3 amended soil. This could indicate that finer WBC particles occupy the pores of the SL soil, resulting in more resistance to penetration and shear strength. A similar pattern was observed by Mapfumo and Chanasyk (1998b) for coal fly-ash amendments: the PR of the CL soils decreased, but the PR of SL soils increased.

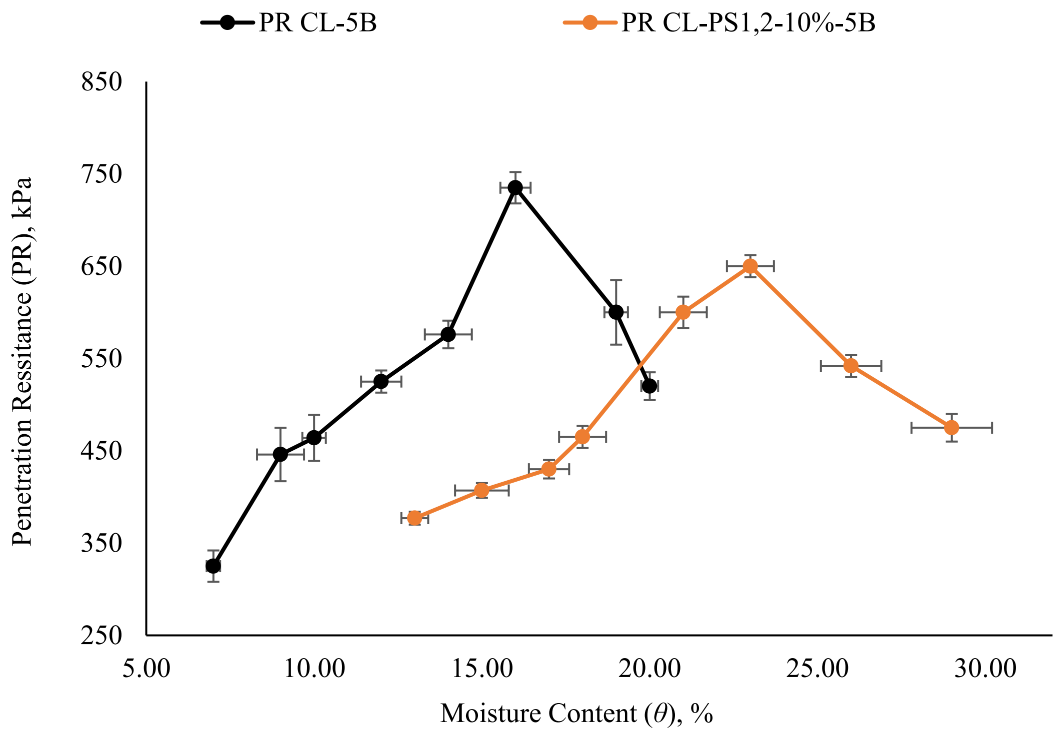

Figure VIII.10: Penetration resistance along the compaction curve of the CL soil (previously compacted with five rammer blows) with and without amendment with 10% WBC PS_1

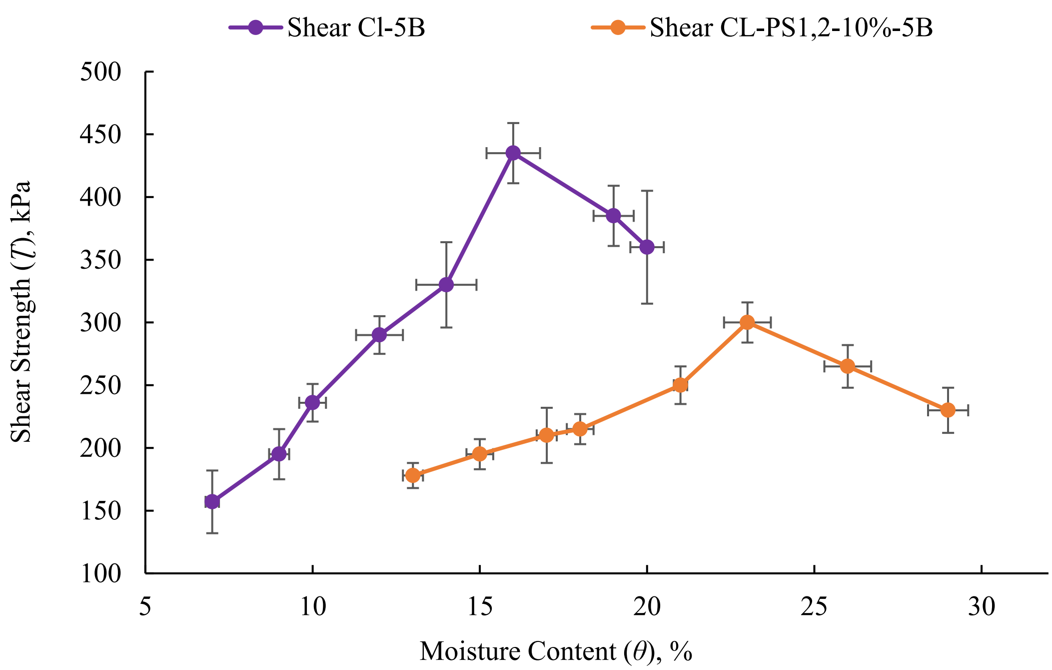

Figure VIII.11: Strength vs. soil moisture of CL soil (previously compacted with five rammer blows) with and without amendment with 10% WBC PS_1

Table VIII.4: The PR_{max} and τ_{max} of sandy loam (SL) and clay loam (CL) soils at two wood-derived biochar dosages

Soil	PR_{max} (kPa)	τ_{max} (kPa)	θ (%)
SL-5B	335±18(a)	275±12(a)	11.5±0.4(a)
SL-$PS_{1,2}$-10%-5B	500±9(b)	365±14(b)	18.5±0.5(b)
SL-PS_3-10%-5B	420±13(c)	300±7(c)	15.0±1.2(c)
CL-5B	735±17(a)	435±24(a)	17.7±0.7(a)
CL-$PS_{1,2}$-10%-5B	650±12(b)	300±16(b)	23.0±0.7(b)
CL-PS_3-10%-5B	700±10(a)	400±11(a)	21.0±0.9(c)

Numbers followed by the same letter implies no difference in the same column

The increase in the PR_{max} and τ_{max} of the SL soil was significant at amendments of 3, 6, and 10% fine WBC. By comparison, as the compaction effort increased, the magnitude of the increase in the PR_{max} or τ_{max} diminished. The PR_{max} and τ_{max} of the amended CL or SL soils occurred at a θ higher than the unamended CL or SL soils at all compaction levels and compositions of WBC in the soils. This was attributed to the higher water affinity of WBC.

Influence of WBC particle size on PR and τ along the compaction curve

Amendment with 10% of the coarser WBC did affect the PR_{max} or τ_{max} of the CL-5B soils (Figure VIII.12).

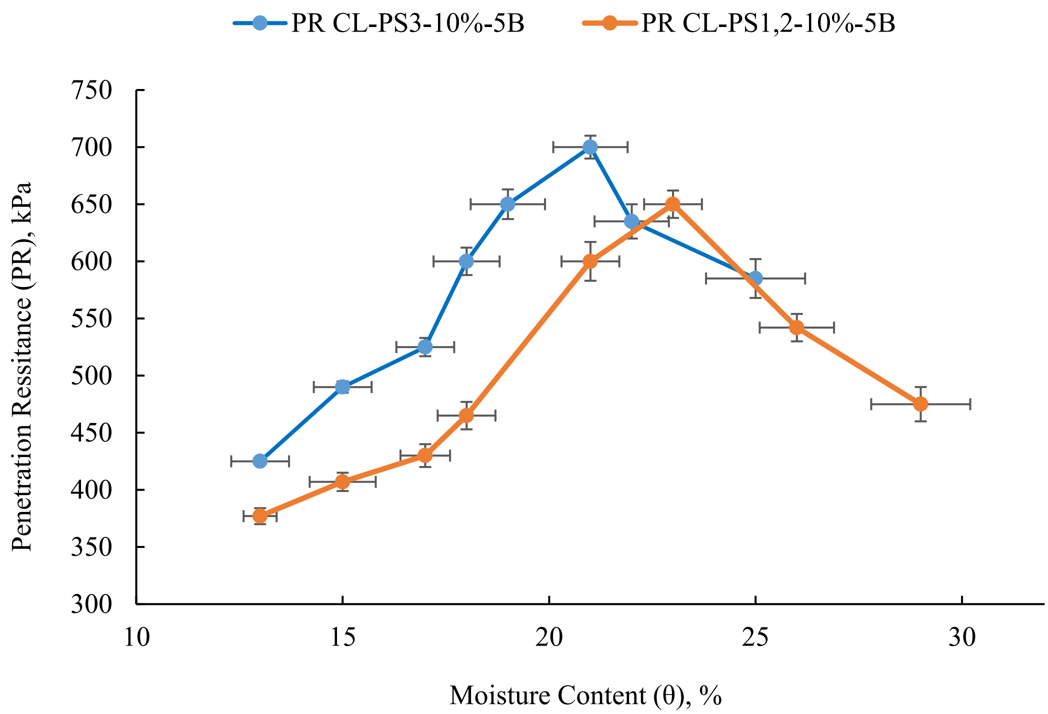

Figure VIII.12: Influence of the amendment with WBC-PS_3 on the PR along the compaction curve of the CL soil after 5 compacting blows

Soil *Ʈ* and *CI* models

The *Ʈ* model constants a_o and r from Equation VIII.5 were determined by the measured values from this research (Table VIII.5). The a_o increased with increased dosages of WBC in the SL soil because the *Ʈ* increased with increased θ_{ll}. The calibrated constants were then regressed against soil θ_{ll} (Table VIII.6). The Ohu (1985) calibrated model could estimate the *Ʈ* of the soil-biochar mix along the compaction curve with R^2= 0.98 (Figure VIII.13). Therefore, from the θ_{ll} of a soil-WBC mixture and the pressure applied to compact the soil, Equation VIII.4 could be used to estimate the *Ʈ* of the compacted soil-WBC mix at any given soil θ. In this project the lower limit of θ_{ll} for the SL and the CL soils were 3 and 7%, respectively. The maximum PR_{max} or $Ʈ_{max}$ occurred at 43 and 38% of the θ_{ll} for the SL and CL soils, respectively.

Table VIII.5: The a_o and r values from Equation VIII.3 for clay loam (CL) and sandy loam (SL) soils amended with 10% fine (0.5–425 µm) wood-derived biochar (WBC). *p* value of slopes is less than 0.001

Soil/Treatment	a_o	r	R^2
SL	131	0.78	0.95
SL-$PS_{1,2}$-10%-5B	253	0.63	0.98
SL-PS_3-10%-5B	187	0.76	0.92
CL	183	1.4	0.95
CL-$PS_{1,2}$-10%-5B	62.8	1.3	0.98
CL-PS_3-10%-5B	149	1.4	0.92

Table VIII.6: Linear relationships between the constants a_o and r from Equation VIII.3 sandy loam (SL) and clay loam (CL) and soil liquid limit (θ_{ll}), *p* values of slopes are less than 0.001

Soil	a_o	r	R^2
SL-$PS_{1,2}$	$a_o = 7.5 \times \theta_{ll} - 63$	$r = -0.008 \times \theta_{ll} + 0.96$	0.91
SL-PS_3	$a_o = 3.9 \times \theta_{ll} + 33$	$r = -0.0013 \times \theta_{ll} + 0.85$	0.89
CL-$PS_{1,2}$	$a_o = -10.5 \times \theta_{ll} + 687$	$r = -0.0095 \times \theta_{ll} + 1.9$	0.91
CL-PS_3	$a_o = -5.2 \times \theta_{ll} + 435.56$	$r = -0.0052 \times \theta_{ll} + 1.66$	0.89

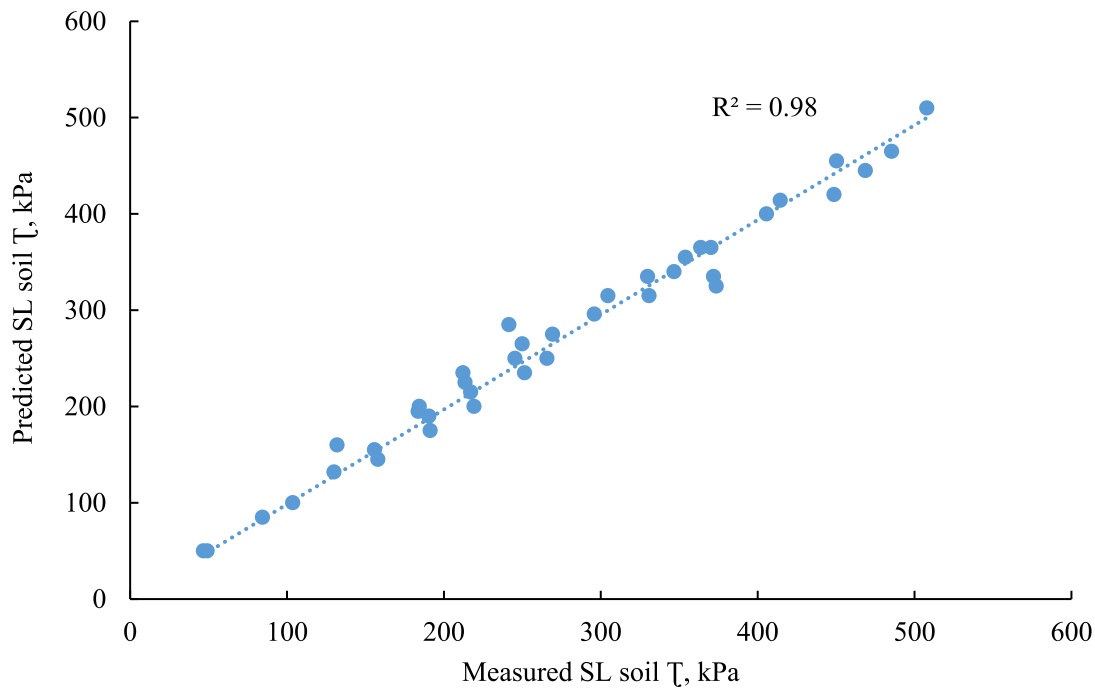

Figure VIII.13: Measured vs. predicted soil shear strength based on the calibrated model of Ohu and Raghavan (1985)

The applicability of the PR model developed by Ohu (1985) was also evaluated. The constants A_1 and n_1 from Equation VIII.2 are presented in Table VIII.7. The slopes of the lines are significant ($p < 0.001$) in all cases. The output of the calibrated Ohu (1985) model for compacted soils amended with WBC was regressed against measured PR values. The regression has a 0.0005 probability level. The Ohu and Raghavan (1985) calibrated model is applicable to the compacted CL and SL soil-WBC mixture: it estimated the measured PR values with a high degree of accuracy (Figure VIII.14).

Table VIII.7: Exponential relationships between the constants A_1 and n_1 from Equation VIII.2 and moisture content (v) of the sandy loam (SL) and clay loam (CL) soils

Soil	A_1	R^2	n_1	R^2
SL-$PS_{1,2}$	$0.99\ e^{28.5v}$	0.98	$-1.43\ v^{-0.6}$	0.94
SL-PS_3	$0.58\ e^{42.6v}$	0.98	$-2.3\ v^{-0.5}$	0.98
CL-$PS_{1,2}$	$4.7\ e^{15.2v}$	0.98	$-1.6\ v^{-0.46}$	0.92
CL-PS_3	$0.01\ e^{60.3v}$	0.95	$-1.3\ v^{-0.77}$	0.98

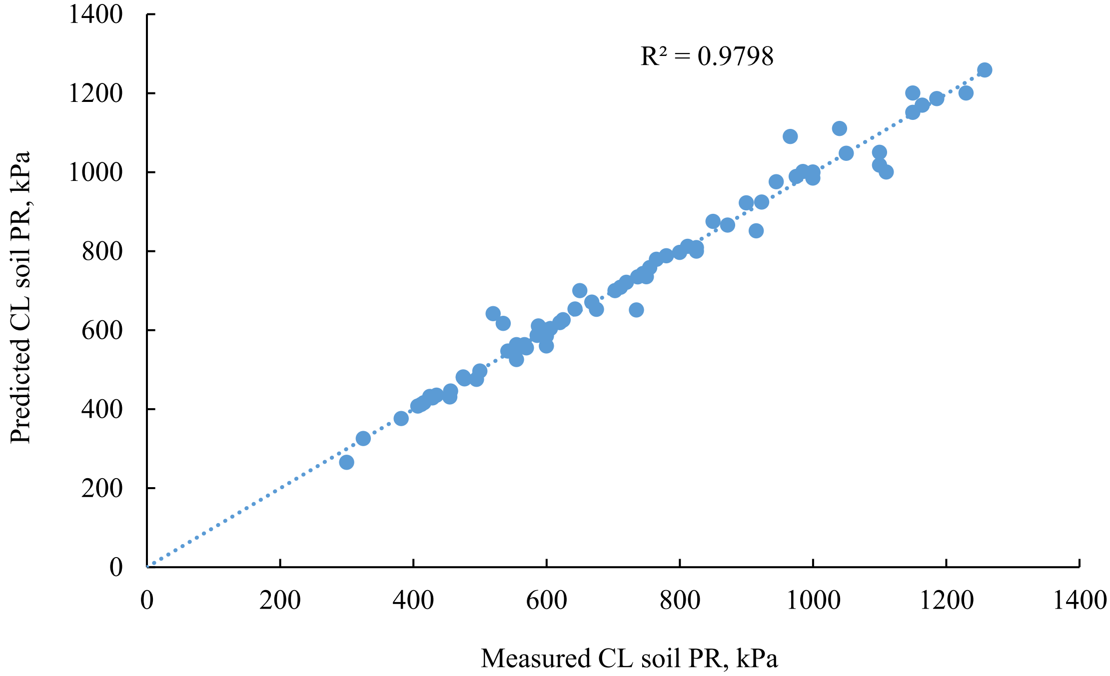

Figure VIII.14: Measured vs. predicted soil penetration resistance based on the calibrated model of Ohu (1985)

also validated their model from field data obtained by Raghavan et al. (1977). The Oho (1985) model had a high degree of accuracy in predicting the state of compacted soils in the field. Therefore, the calibrated Ohu (1985) model presented in this study could be applicable for field application of soil-biochar mixtures.

Tillage requirement

As the SL soil Φ increases, the angles α_c and β decrease, causing an increase in the ρ' values and ultimately the S value to increase. Therefore, the SL soil A_i increases with the increase in the Φ induced by the presence of WBC (Table VIII.8). It should be noted that soil cohesion does not affect the A_i according to the equations presented in Table (VIII.1)—only the angle of internal friction affects the A_i—as it increases due to WBC amendment, the soils A_i increases. The SL soil

A_i increased with the amendment of WBC with no effect of WBC particle size (Table VIII.8). The CL soil A_i increased only with amendment of the $PS_{1,2}$ WBC (Table VIII.8).

The P_{req} was higher for CL soil than SL soil because the τ_{max} and γ were higher in the CL soil. When the SL soil was amended with both fine and coarse WBC, the τ_{max} increased, γ decreased and A_i increased, causing the P_{req} to increase (Table VIII.8). When the CL soil was amended with the fine WBC, the τ_{max} and γ decreased while A_i increased, causing the P_{req} to decrease; no change was observed in the PS_3 amended CL soil (Table VIII.8).

The MR was higher in the SL than the CL soil. The tractor T increases and the MR decreases as a soil has more PR (Equation VIII.22). The SL soil T increased with WBC dosage and with relatively fine WBC. These changes caused the D_{pull} of the SL soil to increase with the dosage and to increase with the decrease in the particle sizes. No changes were observed in the CL soil (Table VIII.8).

Table VIII.8: Results of the tillage requirement, soil disturbed sectional area, and drawbar pull

	Treatments					
	SL	SL-10%-$PS_{1,2}$	SL-10%-PS_3	CL	CL-10%-$PS_{1,2}$	CL-10%-PS_3
P_{req} (hp)	296±11a	562±44b	364±6b	341±6a	301±9b	338 ±12a
A_i (m^2)	0.881±0.055a	0.976±0.028b	0.934±0.035b	0.702±0.018a	0.773±0.030b	0.695±0.010a
D_{pull} (kN)	2.985±0.015a	3.070±0.008b	3.044±0.007c	3.094±0.010a	3.089±0.010a	3.093±0.012a

Numbers followed by the same letter implies no difference in the same column

Conclusions

1. Amendment with the fine WBC affected CL and SL soils differently in terms of PR and τ upon compaction. These differences could be attributed to the differences in the soil ρ following amendment. The PR and τ increased in SL soil because WBC particles occupied soil pores rather than interstices between soil particles, resulting in higher shear resistance.
2. The τ model developed by Ohu (1985) was employed to estimate the compaction state of the soils. The τ model proved useful for quick estimation of the τ of compacted soils,

especially when data are needed on soil-machine-crop interactions. Therefore, if the soil-WBC mixture θ_{ll} is known, along with the stresses imposed on agricultural soils, it's possible to predict the damage due to compaction at any θ.

3. The PR model developed could be used to decide the WBC particle size best suited for a particular soil texture.
4. Even though the SL soil A_i and D_{pull} increased slightly with fine WBC, the P_{req} would also increase, which is not economically feasible. By comparison, the CL soil P_{req} decrease after fine WBC amendment, with minimal changes to soil A_i and D_{pull}. Therefore, the decision of applying relatively fine WBC to a SL or CL soil will depend on other factors such as soil water flow, water retention and aggregate workability.

Connecting Text

Chapters VI to VIII provided information and details of the influence of different particle sizes of WBC on two texturally compacted agricultural soils. **Chapter IX** summarizes the results presented in the earlier chapters and outlines the contribution of new knowledge to this field. The chapter concludes with recommendations that may facilitate future research.

Chapter IX

General Summary and Conclusion

The work began with a study of the compaction curve of an STL soil. The WBC particle size did not affect the ρ_{max} and θ_{opt} (peak of the compaction curves) of the soil. However, the PR and $\mathcal{T}$ measured at the peak of the compaction curves differed, a finding that motivated the rest of the studies.

Two texturally contrasting soils (SL and CL) exhibited different trends on the compaction curve. Amendment with $PS_{1,2}$ or PS_3 WBC decreased the ρ_{max} and increased the θ_{opt} of both SL and CL soils (Table V.2, Figures V.1–V.3). The low dosages (0.5 and 1.75%) of PS_1 WBC did not affect the ρ_o, ρ_{max} or θ_{opt} of the two soil types. The SL soil ρ_{max} was the same at different WBC particle sizes and the θ_{opt} increased with finer particle sizes. The CL soil did not show the same trend as the SL soil. The amended CL ρ_{max} was higher as the WBC particle sizes increased. On the other hand, the CL soil θ_{opt} was minimally affected by amendment with different WBC particle sizes ($PS_{1,2}$ and PS_3 θ_{opt} are near compared to SL where it was highly significant). The θ_{opt} values of CL soils amended with both $PS_{1,2}$ or PS_3 were higher than the unamended CL soil. These variations in the behaviour of different textured soils with varying WBC particle sizes could also be attributed to three things. First, finer particles added to the SL soil confer resistance to compaction because their shape (platted vs. spherical) meant new pores were created in the soil matrix by WBC. Second, the number of particles per unit volume is less for PS_3- than $PS_{1,2}$-amended SL soils. Third, regardless of whether the WBC particles occupied the pore spaces ($PS_{1,2}$) or took the place of soil particles (PS_3), the WBC particle density (0.7 g/cm^3) was low relative to soil particles (2.65 g/cm^3; MacRae and Mehuys, 1985). The variation of the particle density of WBC, which decreases as particles increases-due to lost pores-, likely contributed to the treated soil with different particle sizes have the same ρ_{max} but different θ_{opt} for the CL treated soils and no difference in the treated SL having the same variations in the soil dry ρ.

The workability of the CL soil changed depending on the WBC particle sizes but was not accompanied by changes in the soil fertility.

The water flow in the soils was influenced by the WBC particle size. The relatively coarse WBC had less influence on the soil hydraulic properties. Moreover, the particle size distribution paralleled the water flow behaviour of the amended soils. For example, a decrease in the TP corresponded to a decrease in the water flow, whereas an increase in the TP corresponded to an increase in the water flow in the amended soils.

The SL soil had the same ρ_{max}, when amended with either particle sizes at the same dosage, but the θ_{opt} was higher with the relatively fine WBC. Amendment with coarse WBC led to lower SL soil total pore volume, SP and FC, and AWC but higher k_{sat}, FS and TP than relatively fine WBC. The CL soil had a lower ρ_{max} and near the same θ_{opt}, when amended with relatively fine WBC. The same treatment resulted in higher total pore volume than CL soil amended with relatively coarse WBC. Amendment with coarse WBC resulted in lower k_{sat} and SP than amendment with fine WBC, but the particle size did not affect FS, TP or FC (Table VII.6 and Table VII.2).

Analyses of both the compaction curves and the water filled pores helps to explain the behaviour of the soil amended with various WBC particle sizes upon compaction. The SL-5B total pore volume was 32.3%, whereas it was slightly higher at 37.8% in the SL-$PS_{1,2}$ WBC treatment and 34.9% in the SL-PS_3 WBC treatment. Both amended soils had similar dry bulk densities, which were lower than the SL-5B bulk density. This suggests that the finer (higher density) WBC treatment increased the soil pores to yield same bulk density as the coarser (lower density) WBC treatment. This could be attributed to the fact that when WBC smaller particle sizes ranges lose pores and becomes denser. Also, the relatively fine WBC particles could occupy pores of the SL soil more readily than coarser WBC.

Although the total volume of pores in the SL soil amended with finer WBC exceeded the total volume of pores in the SL soil amended with coarser WBC, the k_{sat} was higher in the former treatment and had lower PR. The pore size distribution analysis revealed that the pores increased in the ranges of FS and TP but decreased in the SP.

The compaction curve PR and SS could be predicted from the θ_{ll} of the soil. Different particle sizes of WBC exhibited different behaviours upon compaction and the PR model developed could be used as a quick tool to gauge the effect of various particle sizes and dosages applied to different textured soils. Theoretically, the tillage requirement for the SL soil will be higher with the finer WBC amendment. The increase in the drawbar pull due to amending the SL soil with fine WBC would be insufficient to negate the increase in the P_{req}.

Contribution to knowledge

First: Methodological

1. The results presented in Chapter V are the first to demonstrate that different WBC particle sizes have the same effect on the compaction curve of a STL soil at dosages up to 10%. The θ_{PL} followed the same trend. The PR and the *Ʈ* at the peak of the compaction curves were lower when relatively smaller WBC particles were amended to the soil.
2. Chapter VIII presents the only published data on the effect of WBC on the PR and *Ʈ* values along the compaction curve for soils amended with varying particle sizes of WBC.

Second: Practical

1. Chapter VI showed that the trend of the compaction curve of the SL soil differs from the CL and STL soils. The W_{agg} of the CL soil was enhanced with relatively fine WBC versus coarse WBC.
2. Chapter VII showed that the water filled pore volume distributions of the SL and CL soils were influenced differently by WBC particle size. When amended with relatively fine WBC, the SL soil FS and TP decreased, whereas the CL soil FS and TP increased.
3. Chapter VII also demonstrated that the soil C emission could decrease if WBC induced changes in the hydraulic properties and density of the compacted agricultural soils.
4. Chapter VIII also developed out a quick tool to estimate the *Ʈ* and PR of compacted agricultural soils amended with varying the particle sizes of WBC. Prediction of the PR of the soils is applicable from predetermined soil properties such as θ_{ll}. The PR model developed could be used to select the particle size suitable for a specific soil texture.

5. The tillage requirements presented in Chapter VIII are the first theoretical analyses for biochar amended soils. This study showed that variation in WBC particle sizes could affect tillage requirements based on the soil texture.

Chapter X
General recommendation

This study focused on the WBC particle sizes variations as they affect soil physical and mechanical properties. The following recommendations are offered for future research.

1. To achieve the desired pore sizes distribution and mechanical behaviour, biochar particles should be engineered to a particle size similar to that of a clay particle (*i.e.,* 1 nm) and particles shaped that are rounded *vs* platted.
2. A study on the pore sizes distribution along the compaction curve will be helpful to estimate the influence of WBC on the water flow and retention of compacted soils.
3. More experiments on soil mechanical studies as amended with WBC such as the triaxial shear testing, which would be beneficial to help understand soil behaviour under compaction.
4. Field studies should be conducted to measure the influence of WBC particle size on the farmland. This is a necessary research avenue to optimize WBC particle size to achieve the desired result (for example in terms of carbon emissions, tillage requirements, infiltration, and crop productivity) and prevent detrimental effects on soil behaviour.
5. Explore the 'social acceptability' of these studies with farmers.

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