Norwegian University
of Life Sciences

Master's Thesis 2023 60 ECTS
Faculty of Environmental Sciences and Natural Resource Management

Effect of Conservation Agriculture and Biochar on Soil Hydraulic Properties in a Ugandan Plinthosol

Adrian Røed Østby
Environment and Natural resources

Acknowledgements

This master thesis marks the end of 2 great years at NMBU as a student under the Faculty of Environmental Sciences and Natural Resource Management. A total of 5 years in academia has provided me with increased knowledge, new personal connections, and a more nuanced way of reasoning.

To say I got adequate support throughout this thesis would be an understatement. I would like to express my sincerest gratitude towards the dedicated and motivating main supervisor Dr.Vegard Martinsen and co-supervisors Prof. Jan Mulder and Prof. Attila Nemes. I have been fascinated and impressed by your extensive knowledge and commitment to supporting students. Additionally, I am also very grateful for the opportunity to travel to Uganda where I conducted my fieldwork and as well participated in a summer school. A massive thank you to Alfred Obia, Talent Namatsheve and Barbara who organized and contributed in the field work.

Many thanks for all nice chats and phenomenal assistance received by lab technician Øyvind Peder Vartdal in the soil physics lab at NMBU, Irene E. Eriksen Dahl, Mona Mirgeloybayat and Byron Spencer in the chemical lab at NMBU.

And as always, I would like to thank my parents for their loving support and motivation through all my years as a student.

Costs associated with analyses, travels and stipend in this thesis were covered by the projects NORPART-2016/10498 (“Academic cooperation on sustainable, climate-smart agriculture between Zambia and Norway”) funded by HK-DIR (Norwegian Directorate for International Collaboration in Higher Education) and NORHED II NMBU program 2021-2026, QZA-21/0182 (“Climate smart agriculture in Sub-Saharan Africa”) under the Norwegian Programme for Capacity Development in Higher Education and Research for Development (NORHED II), funded by Norwegian Agency for Development Cooperation (NORAD).

Adrian Røed Østby

Ås, 15.05.2023

Abstract

Conservation agriculture (CA) is regarded as a robust and resilient agricultural practice, able to meet the challenges related to climate change. Conservation farming in combination with biochar (BC) has gained increased interest over the past years as biochar has been demonstrated to improve several soil physical parameters. This study is based on an in-field trial site under a randomized block design with a total of 24, 4 x 3 m plots, located in the Alebtong district, Uganda. Here we assess how treatments of CA, CA with the addition of BC (CA+BC) and conventional practice (Conv.) affect soil water retention, infiltration, soil bulk density (BD) and soil chemical properties. Additionally, a lab trial was conducted at The Norwegian University of Life Sciences to assess the effect of pigeon pea biochar and maize cob biochar on soil water retention.

The in-field results from treatments under CA showed a significant decrease in BD compared to CA+BC and Conv. The plant available water content (PAWC) did not significantly increase in any of the treatments. However, the water content at permanent wilting point was significantly lower under CA as compared to the other treatments. The results from CA+BC treatments were inconclusive due to lack of BC in the soil samples.

Results from the lab trial showed a significant increase in volumetric PAWC under 10 % pigeon pea biochar treatments, compared to maize cob biochar treatments and control. Both types of BC significantly decreased BD. No significant differences were observed between BC particle sizes on PAWC. However, an indication of greater PAWC was noticeable for the finer BC particles for both BC types. There is uncertainty linked to the maize cob biochar treatments, assumed to be a result of inconsistent saturation time and likely the degree of eventual saturation of the samples.

Table of Contents

ACKNOWLEDGEMENTS II

ABSTRACT IV

1 INTRODUCTION 1

2 MATERIAL AND METHODS 6

2.1 In-depth trial site 6
2.2 Experimental setup 6
2.3 Soil sampling: 8
2.4 Preparation of soil samples 8
2.5 Chemical analysis 9
2.6 Physical analysis: 11
2.7 Calculations and visualization 16
2.8 Statistical analysis 18

3 RESULTS AND DISCUSSION 19

3.1 Field excursion 30.01.2023 19
3.2 Soil chemical analysis 20
3.2.1 Soil attributes 20
3.3 In-field effects of conservation agriculture and biochar on soil physical properties 21
3.3.1 Water repellency 21
3.3.2 Soil penetration resistance 22
3.3.3 Infiltration 23
3.3.4 Soil water retention of soil collected at the in-depth trial site 24
3.4 Water retention in soils with different soil/biochar mixing ratios in the lab 26
3.4.1 Biochar hydrophobicity 26
3.4.2 Comparing two biochar types and their effect on soil water retention 26
3.4.3 Does soil water retention differ between different biochar size fractions? 28
3.4.4 Soil water retention affected by biochar dosage 30

4 CONCLUSION 32

5 REFERENCES 33

6 APPENDIX 38

List of abbreviations:

- SSA: Sub-Saharan Africa
- CA: Conservation agriculture
- BC: Biochar
- BD: Bulk density
- PAWC: Plant available water content
- FC: Field capacity
- PWP: Permanent wilting point
- CA+BC: Conservation agriculture with the addition of biochar
- Conv.: Conventional practice
- CEC: Cation exchange capacity
- HWEC: Hot water extractable carbon
- PPBC: Pigeon pea biochar
- PPBCP: Powdered pigeon pea biochar
- MCBC: Maize cob biochar
- MCBCP: Powdered maize cob biochar

1 Introduction

An increased frequency of extreme weather events such as droughts, storms and floods is predicted worldwide due to changes in the global climate (Stott, 2016). These changes may be detrimental for agricultural production especially in developing nations (Malhi et al., 2021, Anderson et al., 2020). Extended periods of drought and altered rain patterns are linked to reduction and failure of crops in parts of the Sub-Saharan Africa (SSA) (Cairns et al., 2013). Decline in productivity may negatively impact the population in SSA due to food insecurity and malnutrition (Fraval et al., 2019). Like in other countries in SSA, smallholder farmers in Uganda depend on rain-fed agriculture. Precipitation is received in a bi-modal rainfall pattern, peaking in March–May and October-December, resulting in two growing seasons per year (Mubiru et al., 2012). As water is one the limiting factors for plant growth it is essential to implement robust and adaptable agricultural systems to withstand the impacts of imminent climate change (Nsubuga and Rautenbach, 2018, Thierfelder et al., 2018) .

Ensuring food security, climate mitigation and climate adaptation are some of the main principles of the umbrella term described as climate smart agriculture (Taylor, 2018). An element within the climate smart agriculture framework is conservation agriculture (CA). The core principles of CA includes minimizing soil disturbance, increase residue retention and the implementation of crop diversity (crop rotation) (FAO, 2022). Adaptation to CA may require some increased labor and initial investments by the farmer e.g. increased workload when herbicides are not used, basin tillage etc., which may result in partial implementation (Giller et al., 2009). However, a meta-study covering 16 countries in SSA found when all principles are implemented, CA has resulted in increased yields, though only slightly greater (4 % for maize) compared to conventional agriculture(Corbeels et al., 2020). Although several studies point towards CA being a viable agricultural practice to withstand predicted climate change (Farooq and Siddique, 2015), there is no consensus in the scientific community, based on factors such as limitation of plant residues, lack of knowledge and availability of fertilizers and herbicides (Palm et al., 2014, Gowing and Palmer, 2008). As the impacts of CA are further investigated, new possible improvements to the system are emerging. The effects of biochar (BC) as a soil amendment have attracted increasing interest in past years.

Biochar is a carbonaceous bi-product produced through combusting organic material with limited access to oxygen (pyrolysis) (Brown and Wang, 2017). Production of BC can be accomplished with relatively modest inputs of labor, investment and knowledge, by utilizing a Kontiki-, or flame curtain kiln (Schmidt et al., 2014). The Kon-Tiki kiln is primarily a cone-shaped soil pit that can be made using a handheld hoe, when the soil is dry (Image 1 a)) (Cornelissen et al., 2016). During the BC production process, the fire pit is continuously fed with dry biomass, at a rate that ensures constant flames above the feedstock (flame curtain) (Image 1 b)). Most oxygen is consumed by the flames, making the lower levels oxygen depleted, thus producing the charcoal product. A potential concern if numerous farmers implement BC production in their practice, is the consumption of nearby natural vegetation as feedstock. Natural vegetation is already in decline in parts of Uganda and increased use may lead to further land degradation (Jagger and Kittner, 2017). A sustainable feedstock may be cropping residues such as maize cobs and woody biomass of pigeon pea, as a substantial amount of crop residue is left unused on the farm (Roobroeck et al., 2019). The BC yield may be about 20-30%, depending on pyrolysis temperature, with the use of dry pigeon pea (*Cajanus cajan* (L.) Millsp.) stems as feedstock (Sahoo et al., 2021).

Image 1: a) *Start of pyrolysis process in a Kon-Tiki flame curtain kiln in Uganda.* ***b)*** *Flames in the pit consume most oxygen before it reaches a lower level of the kiln. Photos by Adrian Røed Østby.*

Biochar amended soils may also increase carbon storage, as BC is typically slow to degrade, thereby contributing to climate change mitigation (Lehmann et al., 2021, Sparrevik et al., 2013). In addition, BC as a soil amendment has been proven to positively influence soil physical parameters such as bulk density (BD), aggregate stability, infiltration rate, and plant available water content (PAWC) on a long-term basis (Obia et al., 2017, Obia et al., 2016, Blanco-Canqui, 2017). Obia et al. (2016) found that BC amended soils under CA practice increased soil aggregate stability and porosity, while reducing soil bulk density at relatively low doses of 1-2% by volume. The soil bulk density can influence movement of water, air and nutrients in the soil (Hao et al., 2008). Since BC is a porous and light material, the BD of BC are usually low and likely lowers soil BD when mixed with the soil. Biochar may as well indirectly affect BD by stimulating soil aggregation (Khademalrasoul et al., 2014, Ouyang et al., 2013, Obia et al., 2016). These soil properties may influence macro and micropores an thereby the infiltration rate (Alhassoun, 2011).

Infiltration can be described as the transport of water into and through the soil profile (Haghnazari et al., 2015). During intense rainfall it is essential that soil has the ability to absorb a sudden water surges, as a low infiltration rate can lead to water ponding, increased erosion, and loss of valuable and scarce plant nutrients in the soil (Wolka et al., 2021, Bashagaluke et al., 2018). Soil erosion by water is predicted to increase from 30 to 60 % by 2070 (Borrelli et al., 2020). A recent global meta-study, by Gholamahmadi et al. (2023), found that application of BC at a median rate of 5 t/ha reduced runoff by 25 % and soil erosion by 16 % (30 % in tropical soils) on average. This was mainly a result of improved soil structure and increased vegetation coverage from biochar induced plant growth. BC produced from wood biomass was found to significantly increase infiltration rate by 1.7 times in a sealing-prone agricultural soil (non-calcareous, sandy loam) as well as significantly lowering the BD (Abrol et al., 2016). Reduced tillage within CA, such as implementing basins, allows inputs such as BC to be applied in the proximity of plant roots, and thus yielding a greater effect with a lower tonnage per hectare (Cornelissen et al., 2013). Moreover, the basin itself also contributes to rainwater harvesting. Given that the basin is recessed a few cm into the ground, a small reservoir is created around the plant accumulating water and providing a longer infiltration time (Gao et al., 2019). This allows for a greater amount of water reaching the plant roots. Under a semi-arid climate, soil water retention and plant available water is especially important to maintain crop productivity (Akwango et al., 2017)

Plant available water content of a soil is defined as the water content between field capacity (FC) (defined at -100 hPa matric potential), where water no longer freely drains and permanent wilting point (PWP) (defined at -15000 hPa matric potential), beyond which most plant roots are unable to extract water from the soil (Veihmeyer and Hendrickson, 1949). Plant available water is an important factor concerning crop productivity and several studies have found that BC amended soils positively influence PAWC. A lab study by Zhang et al. (2021) explored the potential of BC, derived from woody forest residues to increase PAWC in sand, silt loam and clay soil. The study found that BC applied at a rate of 2% (by weight of carbon) increased gravimetric PAWC in all three soils and that BC particle size had little effect on volumetric PAWC, where volumetric water content is the volume of water relative to the total volume of soil and gravimetric water content is the weight of water relative to the weight of soil. However, volumetric PAWC increased only in the sandy soil and as BC has shown to lower the BD of the soil, thus displaying a smaller effect when expressed in volumetric water content. A similar study by Aller et al. (2017) compared the effect of six, fresh and aged, types of biochar on PAWC and soil moisture retention, in three different soil textures. Both fresh and aged biochar increased soil moisture retention in the clay loam soil, had no impact in a silt loam soil, and had variable effects in a sandy loam soil. Only the fresh biochar increased PAWC for the sandy loam suggesting that the influence of BC on PAWC may "wear off" with age. The positive effect of BC depends on soil type, feedstock and pyrolysis methods (Jeffery et al., 2011).

As soil physical properties are influenced by several factors, it is a complex subject and there is no cure-all formula on how to improve them. However, several studies suggest BC may be a promising solution, yet it is important to note that factors such as BC type, site specific environmental conditions and crop requirements, application rate and method of application, need to be accounted for before implementation. There is a limited number of studies exploring the potential of pigeon pea biochar, in varying particle sizes, to increase PAWC. A broadened knowledge on how pigeon pea biochar affects soil water retention may be beneficial in promoting and implementing it in small-holder practices in Uganda. Although CA and BC could be beneficial for small-holder farmers, challenges such as lack of knowledge, increased labor and socio-cultural norms may slow the transition from conventional practices (Kaweesa et al., 2020). Partial and fully adoption of CA, has proven to be successful in certain districts of Zambia where about 65% of the respondents reported a yield increase of 2 t/ha on average after implementation (Kabamba and Muimba-Kankolongo, 2009). Transferring obtained knowledge and experience from studies conducted in Zambia, to Uganda, may assist future research.

However, other climatic conditions, weather patterns and soil types in Uganda will likely provide different results from that of previous studies.

Currently an ongoing project funded by The Research Council of Norway- “Climate smart innovations in agriculture in Uganda: Improved food security, livelihoods and soil carbon”, coordinated by The Norwegian University of Life Sciences (NMBU) seeks to broaden the knowledge on BC as a soil amendment. The project includes a total of 100 farms split between two different agro-ecological zones within Uganda (Lira/Alebtong and Mubende/Mityana districts). Here, on-farm trials compare treatments of CA, CA in combination with BC and conventional practices. One additional controlled in-depth trial was established to assess effects of crop rotation with different legumes in addition to CA, CA with biochar and conventional practices. The research in this thesis is based on the controlled field trial conducted in the Lira/Alebtong district. While several similar studies often involve a high application rate from 10 to 30 t/ha of BC, this study investigates the effects of a lower, more realistic application rate of 4t/ha. Results obtained from field trials usually include a combination of natural and human-induced factors such as climate, soil variability, agronomic treatments etc. Additionally, it is challenging to design and build extensive field experiments that include various BC types, qualities, and application rates. Therefore, a lab trial with artificially built soil samples containing various rates and qualities of BC, was initiated aiming to isolate the effect of different levels of BC on soil water retention.

Research objectives and Study question

The main objective is to determine the effect of CA and CA in combination with BC as compared to conventional practices on physical soil properties and availability of soil water. The following study questions will be addressed:

1. In what way does pigeon pea BC as a soil amendment in combination with CA affect soil water retention, bulk density, and infiltration compared to conventional practice under field conditions?
2. Does the addition of maize cob biochar or pigeon pea biochar have the same effect on soil water retention?
3. Does the sizing of added biochar particles influence soil water retention under lab conditions?
4. How do different biochar application rates affect soil water retention under lab conditions?

2 Material and Methods

2.1 In-depth trial site

The study was conducted at a trial site established in August 2021 under the project “Climate-smart innovations in agriculture in Uganda: Improved food security, livelihoods and soil carbon” (CLIMSMART, NRC nr. 302713). The location of the trial site is in the Alebtong district, Northern region of Uganda, (2°15'39.3"N 33°14'02.7"E) (Figure 1). Land use history is conventional agriculture with annual cropping. Additionally, it was used as a tree nursery site for a short time prior the establishing the experiment. Alebtong district receives annually on average 1300 mm of rainfall, in a bi-modal rainfall pattern, where the amount of rainfall peaks in the periods between March – April and August – October with an annual mean temperature of 24.5℃ (WorldBankGroup, 2022). The soil in Alebtong are albic plinthosols (Isabirye et al., 2004).

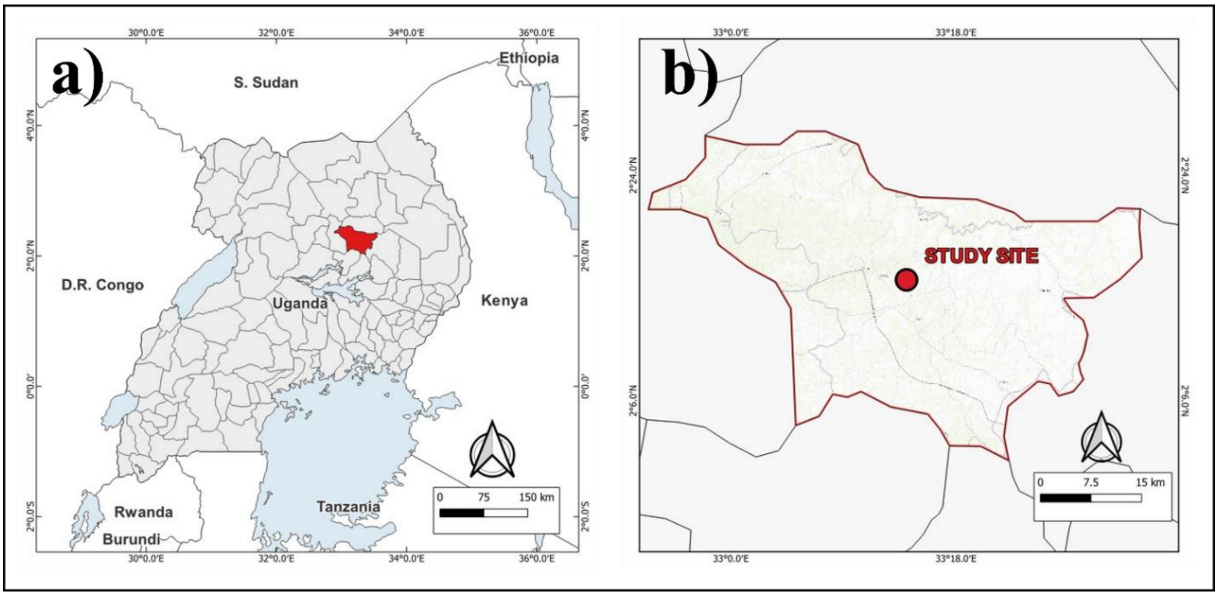


Figure 1: a) Map of Uganda fragmented into districts where Alebtong district is highlighted in red. b) District of Alebtong where red dot indicates location of trial site. The map is generated using the QGIS mapping software (QGIS Development Team, 2022).

2.2 Experimental setup

The experimental setup is a randomized block design consisting of 6 treatments with 24 plots divided into 4 blocks (i.e., 6 treatments in each block). One plot measures 4m x 3m. The 6 treatments include: (1) conservation farming with maize and pigeon pea rotation (CA), (2) conservation farming with maize and pigeon pea rotation and the application of biochar at a rate of 4 t/ha per yr (CA + BC), (3) conventional farming with maize and pigeon pea rotation

(Conv.), (4) conservation farming with soybean rotation (CA+Soy), (5) conservation farming with maize and pigeon pea rotation and the application of biochar at a rate of 2t, 1t & 1t/ha per yr (CA+BC+BC) and (6) conventional farming with maize monocropping (Conv.+Mono/Maize). Investigations in January 2023 revealed that an amount of 3.6 t/ha and 1.8 t/ha of biochar had been added to the treatments CA+BC and CA+BC+BC, respectively when the trial was established. Three treatments were considered in this research: (1) CA, (2) CA+BC and (3) Conv. Plots under CA or CA+BC contain 20 basins, each with 35 cm length, 15 cm width and 20 cm depth. Within-row spacing is 35 cm and between-row spacing is 70 cm corresponding to approximately 20408 basins per/ha (10000/(0.35+0.35*0.7)) (Figure 2). When maize/pigeon pea was planted, each basin received 3 seeds, where the placement was outer edge, center, outer edge of the basin. Plots under Conv. treatments contain regular planting rows with 75 cm between-row spacing and 30 cm within-row spacing of planting stations. When maize/pigeon pea was planted each planting station received 2 seeds. No fertilizer was applied to any of the treatments. The BC applied to the in depth trial site was produced in a Kon-Tiki kiln (Cornelissen et al., 2016), using air-dry pigeon pea stems as feedstock, with an average pH of 9.9, CEC 80.9 cmol/kg, 56 % carbon content.

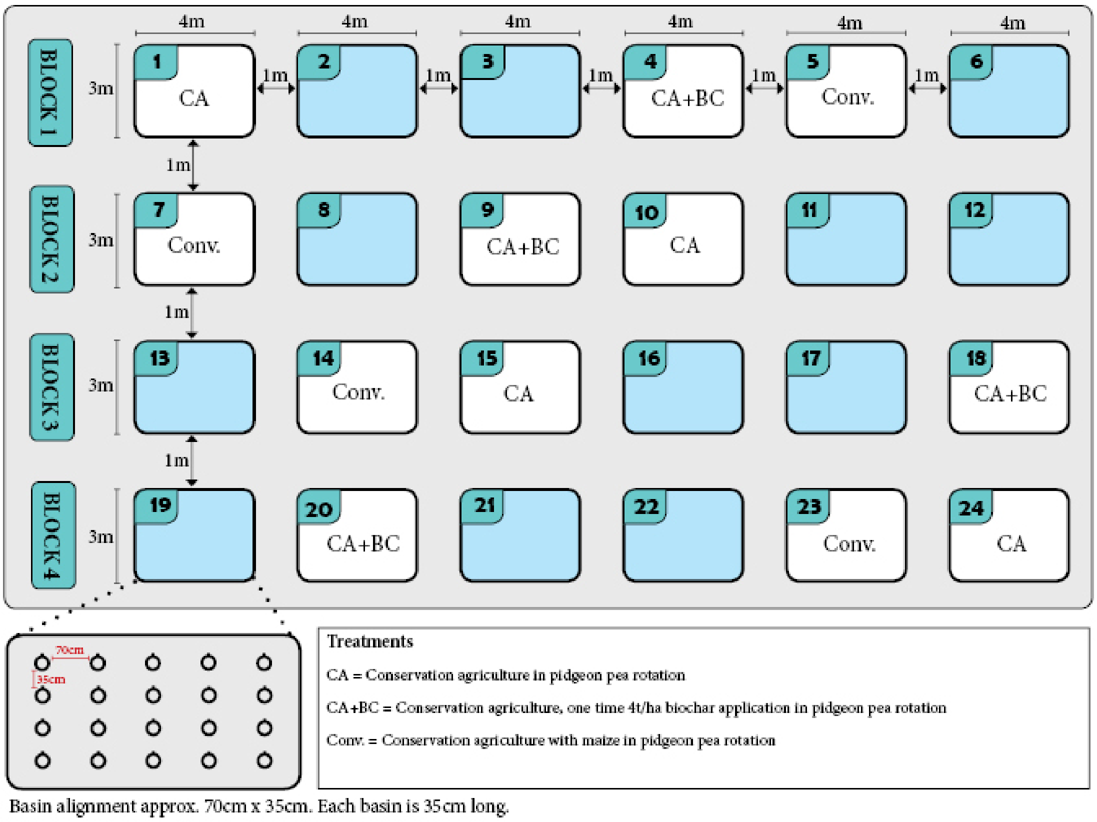


Figure 2: *Experimental setup consisting of 4 blocks with 6 treatments per block. The white boxes represent plots containing treatments analyzed in this thesis. Blue boxes represent plots containing excluded treatments.*

2.3 Soil sampling:

Undisturbed samples

Three basins or planting stations were randomly selected at each of the 12 plots marked in white in Figure 2, resulting in a total of 36 sampling points. Sampling points were randomly chosen within the basin borders at plots containing CA and CA+BC treatments, and within planting rows at plots with conventional treatment. In each case, samples were taken from about 10 cm away from any plant stem. The sample points were prepared by scraping off the topsoil layer (0 – 5 cm). A 3.8 cm (H) x 5.8cm (ID) (100 cm^3) metal ring was driven vertically into the soil by placing another ring on top of it and hitting it with a hammer. When the lower ring was driven beneath the soil surface, the soil surrounding it was removed using a garden spade, resulting in a sampling depth of about 5-10 cm. A trowel was pushed under the ring, and it was pried up from the ground. Any excess soil was scraped off with a knife and the rings were capped off with plastic lids at both ends. The rings were packed and sent to the soil physics lab at NMBU for analysis.

Disturbed samples

One basin or planting station were randomly selected from each of the 12 plots (a total of 12 sampling points). Sampling points were randomly chosen within the basin borders at plots containing CA and CA+BC treatments, and within planting rows at plots with conventional treatment. In each case, samples were taken from about 10 cm away from any plant stem. The sample point was prepared by scraping off the topsoil layer (0 – 5 cm). About 500g of soil was collected from a 5 - 20cm depth using a garden spade. Soil samples were packed and sent to the soil chemical lab at NMBU for analysis.

2.4 Preparation of soil samples

12 plastic bags (1 bag from each plot) containing the disturbed soil samples were placed in a drying cabinet for 48 hours at 55°C. The plastic bags were left open to let the evaporated water escape. When air-dry, the contents of each bag were mixed and transferred to a <2mm sieve (wire mesh, square holes). A pestle was used to work the material through the sieve. All aggregated pieces of soil in the sample that did not pass through the sieve were placed in a cardboard container and crushed with the pestle and then re-sieved. A subsample of the sieved material was further crushed in a Retsch RM 200 mechanical agate mortar (VERDER International BV, Netherlands, Vleuten). The mortar ran for 4 minutes for each sample. To

prevent cross contamination of the samples, the mortar was cleaned by running pure sand in between samples.

2.5 Chemical analysis

pH in water

10 ml of sieved soil (<2 mm) was transferred to a plastic beaker using a 10 ml volume measuring cup. 25 ml of de-ionized water was transferred to the bottle using a dispenser. The beaker was then shaken for about 10 seconds and then rested. After 1 minute, the beaker was shaken again then allowed to stay overnight. Next day the beaker was shaken 2 more times for about 10 seconds and left to sediment for 10 minutes. The pH was then measured using a PHM210 Standard pH meter (Radiometer Analytical SAS, Villeurbanne Cedex, France) calibrated with a 4.00 and 9.00 buffer.

Cation exchange capacity

Determination of cation exchange capacity (CEC) was based on the method described by Schollenberger and Simon (1945). 3.00g of sieved (<2mm) soil was weighed into a 100ml Erlenmeyer flask. Then 25ml, 1M ammonium acetate (CH_3COONH_4) at pH 7.00 was added to the flask, the flask was swirled for about 10 seconds and then left to stand overnight. The solution was filtered through <2 µm Whatman Blue ribbon filters that were prewashed with 0.1 M ammonium acetate. 7 ml of the filtrate was then transferred to test tubes and sent to analysis of magnesium (Mg), calcium (Ca), sodium (Na) and potassium (K) using ICP OES, at the NMBU lab. To determine extractable acidity, 20 ml of the filtrate was transferred to a plastic container. The container was placed on a stir plate and the pH was measured. The solution was back titrated with 0.05M NaOH until the solution reached pH 7.00. Potential CEC (cmol/kg) is described as the sum of H^+ and exchangeable base cations.

Hot water extractable carbon

Determination of hot water extractable carbon (HWEC) was based on the method described by Ghani et al. (2003). 4.5g of sieved soil (<2mm) was weighed into a 50 ml centrifuge tube, and 45ml of deionized water was added to the tube. All tubes were shaken by hand for about 1 minute. The tubes were then placed in a tub of water heated to 80°C and left to stay for 16 hours. The tubes were removed from the tub and centrifuged for 10 minutes at 4500 rpm. About 15 ml of the centrifuged solution was passed through a filter tip syringe into test tubes. The samples were then analyzed for dissolved organic carbon (DOC) using a SHIMADZU TOC V Total Organic Carbon Analyzer (Shimadzu Corporation, Japan, Kyoto) at the NMBU lab.

Tot carbon and nitrogen content

Total carbon (C) was determined by the dry combustion method described by Nelson and Sommers (1983). Total nitrogen (N) was determined by the "Dumas" method described by Bremner and Mulvaney (1982). Total C and N were analyzed using Leco CHN628 Elemental Analysis by Combustion (LECO Corporation, USA, Saint Joseph, MI).

Inorganic, organic, and total phosphorus content

Determination of total and inorganic phosphorus (P) was done according to Møberg and Petersen (1982). Two subsamples of 1.00g of crushed soil were weighed. One of the subsamples was ignited at 550C for 1 hour. Both samples were transferred to separate Erlenmeyer flasks and 5ml 12 M H2SO4 was added. The flasks were heated to 70°C for 10 minutes. An additional 5ml 12 M H2SO4 was added. The solution was diluted by adding de-ionized water until the total volume reached 250ml. The ignited sample represents the total P concentration. Organic P was determined by calculating the difference between total and inorganic P.

P-AL

Phosphorus was determined using the ammonium lactate (AL) extraction method according to Egnér et al. (1960) to assess the amount of plant available P in the soil. 2.00g of sieved (<2mm) soil and 40ml AL extraction solution was transferred into to a 100 ml glass bottle. The bottle was placed on a shaker table at 110 oscillations per minute for 90 minutes. The solution was filtered through <2 μm Whatman Blue ribbon filters, prewashed with AL extraction solution. The samples were analyzed by ICP-OES

Ammonium oxalate extraction

Aluminium (Al) and iron (Fe) oxides was determined using the ammonium oxalate extraction method based on Parfitt (1989). 1.00g of sieved soil (<2mm) and 50ml OX extraction solution were transferred into a 100ml glass bottle. The bottle was placed on a shaker table at 110 oscillations per minute for 240 minutes, in darkness. The solution was filtered through <2 μm Whatman Blue ribbon filters, prewashed with OX extraction solution. The samples were diluted 10x and analyzed by ICP-OES.

2.6 Physical analysis:

Water repellency

Water repellency was determined by measuring water drop penetration time (WDPT) in-field based on procedure described by Letey et al. (2000). The area was selected randomly within the borders of the basin at plots containing CA and CA+BC treatments and about 10 cm out from plant stem in plots containing conv. treatment. 5 cm of the topsoil was removed in an area of about 10 cm x10 cm. 10 drops of water were dropped randomly inside the area using a plastic 10 ml plastic pipette. The time between the droplet contacting the soil and it was fully absorbed by the soil was recorded. The soil was air dry on the soil surface and slightly moist at 5 cm depth.

Soil penetration resistance

Soil penetration resistance was measured using a Royal Eijkelkamp pocket penetrometer (Royal Eijkelkamp, The Netherlands, 6987 EN Giesbeek). A 40 cm deep soil profile was excavated at the edge of all 12 plots (intersecting basins at CA and CA+BC treatments). 5 measurements were made per depths of 5, 10 and 30 cm. The penetrometer was pushed horizontally into the wall of the soil profile and the resistance reading was recorded. The resistance values in kg/cm^3 recorded on the pocket penetrometer were converted to kPa using the following formula in (1):

$$Resistance\ (kPa) = \frac{Resistance\ force\ (kg/cm^3) * 98066.5}{1000} \quad (1)$$

Infiltration

A Mini Disk Infiltrometer (METER Group, Inc. USA, Pullman, WA) was used to measure the infiltration rate at near-saturation in-field (Image 2), from which the near-saturated hydraulic conductivity was calculated. The infiltration rate was measured at -2 cm and -4 cm pressure. By infiltrating water under tension, the Mini Disk Infiltrometer minimizes the effect of macro pores (METER Group, 2021).The top layer (0-2 cm) of soil was scraped off using a garden spade. This was done to ensure sufficient contact between the soil and the infiltrometer. Three basins or planting stations were randomly selected within each plot. The infiltrometer was placed within the border of the basins or in planting rows, and about 10 cm away from the plant stem. The infiltrometer was filled with water, and the volume was recorded. Timing by a stopwatch was started when the infiltrometer was placed on the soil surface. Infiltrated water volumes were read at set time intervals. If the infiltrometer ran out of water before the measurements were completed, the infiltrometer was replaced with a full infiltrometer during the measurement, and the measurement was continued. The hydraulic conductivity calculations were made using the made-for-purpose spreadsheet distributed by the manufacturer (METER Group, 2021).

Image 2: *Mini Disk Infiltrometer in use at -4 cm pressure. Photo by Adrian Røed Østby.*

Water retention, in-field soil samples

Undisturbed soil samples (36, 100cm^3 rings) were prepared for pF determination in the soil physics lab at NMBU following the procedure of Klute (1986).

Some rings were not filled completely due to incorrect sampling which would result in an incorrect calculation of the BD (Image 4). The missing volume of the rings was estimated based on pore volume measurements that are described in further detail later in this chapter.

<u>Sample saturation</u>

The undisturbed soil samples were prepared by securing a porous nylon cloth on one end of the ring with a rubber band and placing them in a plastic tray. The tray was then gradually filled with water over 6 days to saturate the samples from bottom to top. After saturating the samples, their weight (+ring + cloth + rubber band) was recorded. The rings were suspended above the tray for 3 seconds before placed on weight to let excess water drain.

<u>Sandbox</u>

The wet end of the pF curve was measured using the sandbox method. After saturation, the samples were placed in a Royal Eijkelkamp sandbox for pF determination (Royal Eijkelkamp, The Netherlands, 6987 EN Giesbeek). We equilibrated the samples at -10hPa (6 days), -20hPa (4 days), -50hPa (6 days), -100hPa (7 days), suctions successively. The samples were weighed after equilibration at each suction.

Pressure chamber

All other points on the pF curve were measured using the pressure plate method. Ceramic membranes that had been left to saturate for > 24 hours were placed in a 5 or 15 bar pressure plate extractor (Soil moisture Equipment, Santa Barbara, CA). Twelve samples were placed on top of each ceramic plate, and within its borders. A gentle nudge was given while placing the ring to ensure good contact between its contents and the ceramic plate. The chamber was then sealed and pressurized at 100hPa (and equilibrated for 7 days), 330hPa (8 days), 1000hPa (18 days), 3000hPa (17 days), successively. The samples were weighed after equilibration at each pressure.

For -15000 hPa measurements small plastic rings were placed in a high-pressure pressure chamber. A subsample of about 2 teaspoons of soil from disturbed soil samples was transferred to the small plastic ring, wetted, and equilibrated for 19 days. The samples were weighed after equilibration.

Drying

After all the above measurements were completed, each ring and soil sample was transferred to a plastic container. The weights of the cloth and rubber band were recorded and were to be added to the final weight after drying, since they were part of the tare weight throughout the wet measurements. The plastic containers were put in the drying oven to dry at 105C for 3 days and their weight was recorded.

Air filled pore volume

Air filled pore volume was determined immediately after weighing the samples that have been equilibrated at 100hPa and 330hPa in the pressure chamber. An air pycnometer was used for the purpose, where a rubber seal was placed on top of the core ring and the ring was turned upside down and the rubber band and cloth were removed. A cover was placed over the ring, creating a small chamber that is connected to the air system. Pressurized air (1 bar) was released into the system and allowed to expand. The loss of pressure was recorded after equilibration and used to infer the volume that it expanded to. To calibrate the system, pre-manufactured metal disks of known volume were placed to gradually fill a previously empty sampling ring, the known “pore volumes” and the corresponding equilibrated pressures were logged. A calibration curve was fitted to these calibration data and was then used to infer the air-filled pore volume of each soil sample from their pressure readings. We completed this measurement after the samples were equilibrated at 100hPa and 330hPa in the pressure chamber, giving us a chance to approximate the total pore volume as the sum of the air filled and water filled porosity at each pressure.

Water retention, artificially build samples

The experiment setup consists of 45, 4.0 cm (H) x 3.5 cm (ID) (38.4 cm^3) plastic cylinders containing artificially built soil samples of 5 different materials: 1) Sand, <2mm fraction size; 2) pigeon pea biochar, <2mm fraction size (PPBC); 3) pigeon pea biochar powdered, ground in mortar (PPBCP); 4) maize cob biochar, <2mm fraction size (MCBC); 5) maize cob biochar powdered, ground in mortar (MCBCP).

Moisture content and bulk density of the samples

Moisture content and BD of each material was determined before calculating mixing ratios for the samples. Sand/BC was transferred to a plastic cylinder. When filled completely the cylinder was gently tapped 3 times on 4 sides with a spoon and then lifted gently up and down to allow for the material to settle. Any free remaining space in the cylinder was backfilled and excess material (above edge of cylinder) was scraped off using the straight edge of the spoon. The contents of the cylinder were poured into pre-weighed aluminum tray and the weight was recorded (wet weight). The trays with all 5 materials were placed in a drying oven at 105°C for 24 hours and the weight was recorded (dry weight). Moisture content was calculated using formula in (3) and BD using formula in (4)(3).

Biochar hydrophobicity

5 drops of deionized water were dropped onto to each type of BC held in a plastic container. The time between application and complete absorbance of the droplets were recorded.

Determining mixing ratios

The initial water content of the BCs was accounted for when determining mixing ratios of sand and BC. Mixing ratios was calculated for 2 %, 5%, 10%, 50%, and 100 % BC dosages (only 2 % and 50 % for PPBCP and MCBCP) on a volumetric basis.

Mixing of material

Mixing was done by weighing calculated amounts of BC and sand separately in a tared aluminium tray. The contents of the tray were poured into a zip lock bag. The bag was turned over several times until the material was thoroughly mixed. As the heavier sand particles tended to sink to the bottom of the bag among the larger and lighter BC particles, the bag was remixed in between filling of each ring to ensure homogeneity of the media. Filling and compaction of the rings was done according to the process explained under MC determination. The weight of the first sample was recorded and the same amount of soil/BC mix was added to the remaining 2 samples making all 3 replicates the same weight.

Saturation

The samples were let to saturate for 3 days with a cloth and rubber band secured at both ends. The ring was lifted out of the tub and the upper (red) cloth was removed. The ring was suspended above the tub to let water drain for about 3 seconds (Image 3 c)).

Sanbox and pressure chamber

The process equilibrating the samples at each pF step were the same described under “pF soil“. Samples were equilibrated in the sandbox at -10hPa (5 days), -20hPa (8 days), -50hPa (7 days), -100hPa (7 days), pressures successively. Samples were equilibrated in the pressure chamber at 100hPa (7 days), 330hPa (8 days), 1000hPa (11 days), 3000hPa (15 days) pressures successively (Image 3 b), d)).

For the -15000 hPA measurements, a subsample from each soil+BC mix was transferred to a 50 ml plastic tube. The tube was filled with deionized water and agitated. After saturating for 7 days the contents of the tube were filtered through a cloth to remove excess water. The filtrate for each sample was mixed until homogeneous as the sand and BC was partially separated after filtration (Image 3 a)). Thereby it was transferred to a small plastic ring placed on the pressure plate. The contents of the rings were made slightly wet in order to make the material settle. The samples were equilibrated at -15000 hPa for 23 days.

Drying

After all the above measurements were completed, each cylinder and plastic containers (15 bars) were put in the drying oven to dry at 60C for 5 days and their weight was recorded.

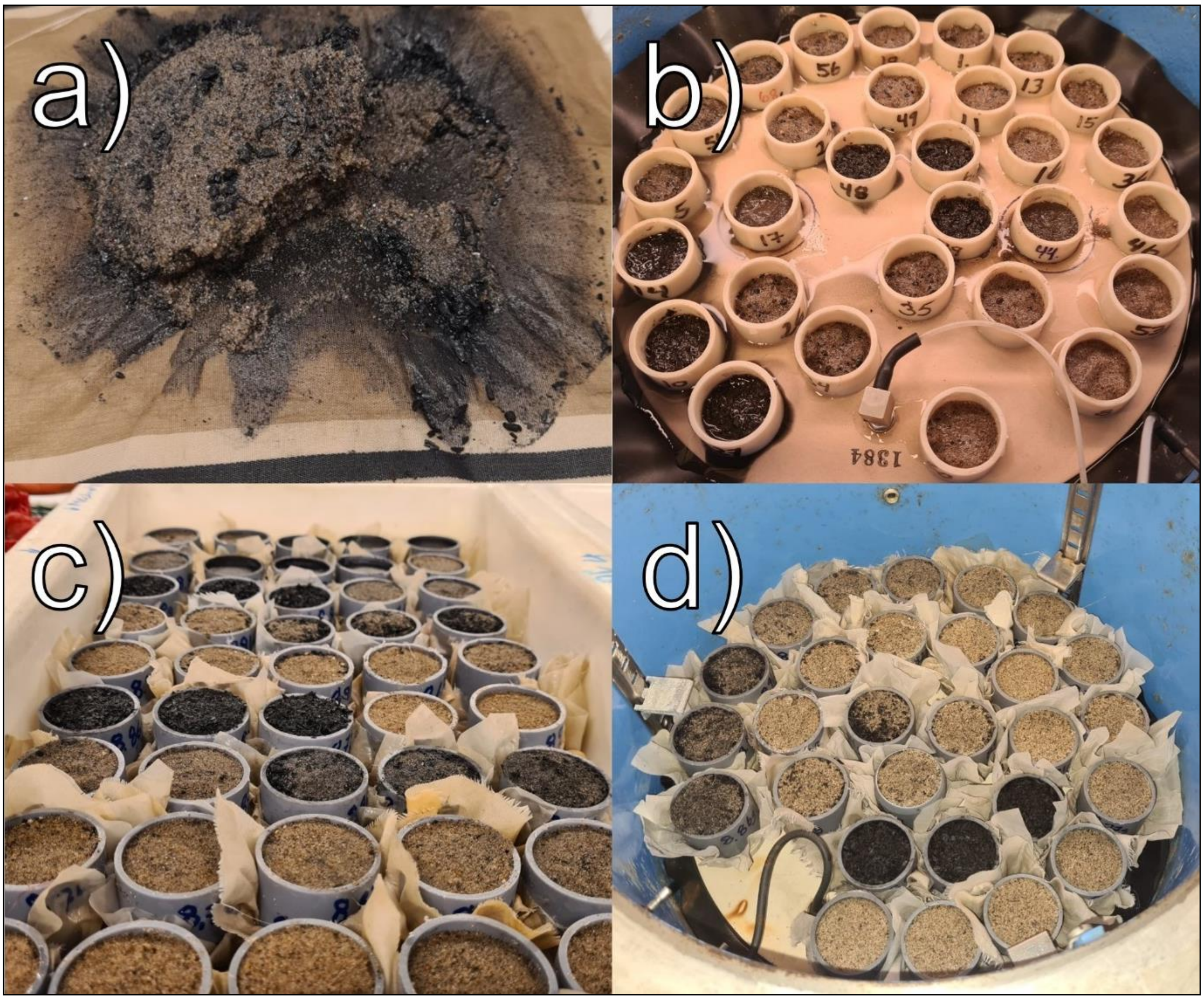


__Image 3: a)__ Saturated subsample set for -15000 hPa pressure, __b)__ Subsamples placed on pressure plate prior to -15000 hPa (PWP) equilibration, __c)__ Saturated samples with different soil/biochar mixes, __d)__ Samples placed on pressure plate prior to -100 hPa (FC) equilibration. Photos by Adrian Røed Østby..

2.7 Calculations and visualization

Missing volume estimation

Some rings were not filled completely due to incorrect sampling which would result in an incorrect calculation of the BD (Image 4). The free space in the rings was estimated based on pore volume measurements. Pore volume of the soil in the rings was calculated by subtracting weight of soil at -330hPa, from weight of soil at saturation. The calculated pore volume of the soil was then subtracted from the total pore volume of the ring, measured by the pycnometer thus giving an estimate of the volume of free space in the ring. Free space of the ring was calculated using formula in (2):

$$Free\ space\ (\%) = Measured\ pore\ volume\ (\%) - Calculated\ pore\ volume\ (\%) \tag{2}$$

Image 4: *Example of core rings with varying levels of missing soil. Photo by Adrian Røed Østby*

Fitting retention curves

Fitting of retention curves was completed using the RETC Program (Van Genuchten et al., 1991). The model was set up in the following order: "Retention Data Only" was chosen as the type of problem, default time and space units were used, van Genuchten with m = 1-1/n and 10 data points was selected as the type of retention/conductivity model, sandy loam was chosen as the water flow parameters, and retention curve data from the lab was imported for volumetric water content at various pressure heads (-10hPa, -20hPa, -50hPa, -100hPa, -330hPa, -1000hPa, -3000hPa, -15000hPa).

To fine-tune the fitted curve an additional data point at -15000000hPa was added to the model. Volumetric water content at this data point was manually adjusted to obtain the best fit of the curve (R-squared ≈ 1). The values of the output parameters (ThetaR, ThetaS, Alpha, n) were entered in a made-for-purpose spreadsheet provided by Kværnø (2023). Retention curves for “average” curve for each treatment were fitted by first calculating the mean of the retention data from lab measurements for each treatment at each pressure in an excel sheet, followed by the abovementioned fitting process in RETC.

Calculations

Gravimetric water content was calculated using formula (3):

$$Gravimetric\ water\ content\ (g/g\%) = \frac{Weight\ of\ wet\ sample\ (g) - weight\ of dry\ sample(g)}{Weight\ of\ dry\ sample\ (g)} * 100$$

(3)

Bulk density was calculated using formula (4):

$$BD\ (g/cm^3) = \frac{Weight\ of\ dry\ sample\ (g)}{Volume\ of\ ring\ (cm^3)}$$

(4)

The volumetric water content was calculated using formula (5). The density of water is assumed to be 1 g/cm^3:

$$Volumetric\ water\ content\ (v/v\%) = gravimetric\ water\ content\ (g/g\%) * BD\ (g/cm^3)$$

(5)

Plant available water content was calculate using formula (6):

$$PAWC\ (\%) = volumetric\ water\ content\ at\ 100\ hPa\ (v/v\%) -\ volumetric\ water\ content\ at\ 15000\ hPa\ (v/v\%)$$

(6)

2.8 Statistical analysis

Statistical analyses were performed using the statistical software R (R Development Core Team, 2022). Plotting was done using ggplot2(Wickham, 2016). Certain code lines were generated using the artificial intelligence chatbot, ChatGPT (OpenAI, 2023). One-way analysis of variance (ANOVA) with blocks (four) was used to test for differences between treatments (three levels) at a level of significance $p < 0.05$. If the F-test (i.e., the treatment variance divided by the error variance) was significant, thus rejecting the null hypothesis that treatments were the same, the Tukey honest significant difference test (Tukey HSD) was applied to determine which of the treatments were significantly different. Significant differences were assumed at $p < 0.05$ for the Tukey HSD test.

3 Results and discussion

3.1 Field excursion 30.01.2023

A field excursion on January 30th, 2023, was organized and completed by members of the team, where the setup of the in-depth trial site was assessed. The assessment revealed that BC had not been fully mixed with the soil within the basins at CA+BC plots (Image 5). Additionally, when opening the basins, it became apparent that the BC was aggregated in solid lumps and only present at approximately 20 cm depth and deeper. Considering the depth of soil sampling from 0 to 20 cm depth, it was clear that only small amounts of BC had been captured in the soil samples analyzed in this thesis, resulting in soil samples not representing the actual amount of BC added. This discovery has affected results from plots under CA+BC treatment, thus yielding unexpected values from the measurements and analysis.

Image 5: *In the CA+BC basins the biochar was not mixed in thoroughly, but instead was found in lumps. a) Clump of congregated biochar. b) Example of concentrated biochar deep in the basin. Photo by Vegard Martinsen.*

3.2 Soil chemical analysis

3.2.1 Soil attributes

No significant difference was found in Total C and HWEC concentration. The theoretical Total C content in CA+BC treatments should be on average 0.63 ± 0.16 % higher if all added BC (176 g/basin) had been homogeneously mixed into the soil. There was no significant difference between treatments on the soil attributes in Table 1, except for Organic P where the concentration was significantly higher in Conv. compared to CA.

***Table 1:** Mean soil attributes from in-depth experimental site in Alebtong (sampled June 2022) where ± corresponds to standard error (n=4 each treatment). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05).*

Treatment	CA	CA+BC	Conv.
pH	7.12±0.20 a	7.15±0.16 a	7.02±0.18 a
CEC (cmol/kg)	14.6±1.06 a	14.91±1.98 a	15.05±0.97 a
HWEC mg/kg	470±30.00 a	460±25.82 a	500±34.64 a
Tot.C (%)	1.62±0.10 a	1.78±0.14 a	1.72±0.06 a
Tot.N (%)	0.12±0.00 a	0.12±0.01 a	0.13±0.01 a
Tot.P (mg/kg)	593±39.87 a	613±66.63 a	655±68.37 a
Inorg.P (mg/kg)	413±45.53 a	423±60.33 a	443±65.75 a
Org.P (mg/kg)	180±7.07 b	190±8.16 ab	213±6.29 a

CEC = Cation exchange capacity; HWEC: hot-water extractable carbon; Tot.C = Total carbon content in the soil; Tot.N = Total nitrogen content in the soil; Tot.P = Total phosphorus in the soil; Inorg.P = Inorganic phosphorus in the soil ; Org.P = Organic phosphorus in the soil

A higher concentration of Tot.C and HWEC was expected in the CA+BC treatments similar to other studies (Munera-Echeverri et al., 2022, Demisie et al., 2014). Additionally, we would have expected an increase in pH and CEC (Martinsen et al., 2015). Biochar, depending on type, has also indicated an increase of soil available P in various soil types (Gao et al., 2019), still there was no difference among the treatments. The concentration of K lowest under CA+BC treatment (Appendix 2). We would have expected a higher concentration of K as it is linked to BC addition (Martinsen et al., 2014). An increase in active amorphous oxides were expected but was not found (Appendix 1). Small or no differences in CA+BC treatments, especially

Tot.C, demonstrated that is highly likely that no BC was present in the disturbed soil samples. This finding supports what was observed during the field excursion on January 30th, 2023, which made clear that the BC was not fully mixed inside the basins at CA+BC plots (Image 5). This would also have implications for the undisturbed samples captured in core rings, as they were collected at a shallow depth of approximately 10 cm.

3.3 In-field effects of conservation agriculture and biochar on soil physical properties

3.3.1 Water repellency

No water repellency was detected within any of the treatments (Table 2). As all droplet penetration measurements at both 0 cm depth (surface) and 5 cm depth resulted in 1 second or less, no statistical analysis was conducted, or standard error visualized.

Table 2: *Mean water droplet repellency time measured at in-depth experimental site in Alebtong (measurements conducted June 2022) where ± corresponds to standard error (n=120 each treatment). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). No statistical analysis is done as all measurements were 1 second or less.*

Treatment	CA	CA+BC	Conv.
Repellency time (s) 0 cm depth	1 ± 0	1 ± 0	1 ± 0
Repellency time (s) 5 cm depth	1 ± 0	1 ± 0	1 ± 0

Hydrophobicity is most commonly observed in dry soils and may decrease as moisture content increases (Doerr et al., 2000). The measurements were done during the rainy season and the soil was moderately moist. Thus the “true” water repellency of the soil may be higher at a lower moisture content. As there is a low soil water droplet repellency time in all treatments the soil can be classified as a wettable soil according to (Dekker and Jungerius, 1990). The low water repellency may as well be a result of recent soil disturbance in the plots which may eliminate factors such as build-up of hydrophobic materials in the soil crust. Nevertheless, this finding is optimistic as hydrophobic soils are prone to initiate preferential flow patterns through the soil matrix which may lead to an uneven distribution of both water and nutrients to the plant roots (Liu et al., 2017). Additionally, a wettable soil has a positive effect on water infiltration rates in sand/silt loams where high water repellency could greatly decrease the infiltration rate (Yi et al., 2018, York, 1993).

3.3.2 Soil penetration resistance

There was no significant difference in soil penetration resistance between treatments at 5cm, 10 cm and 30 cm depths visualized in Figure 3. A tendency of lower penetration resistance in 10 cm and 30 depths under CA treatments can be seen.

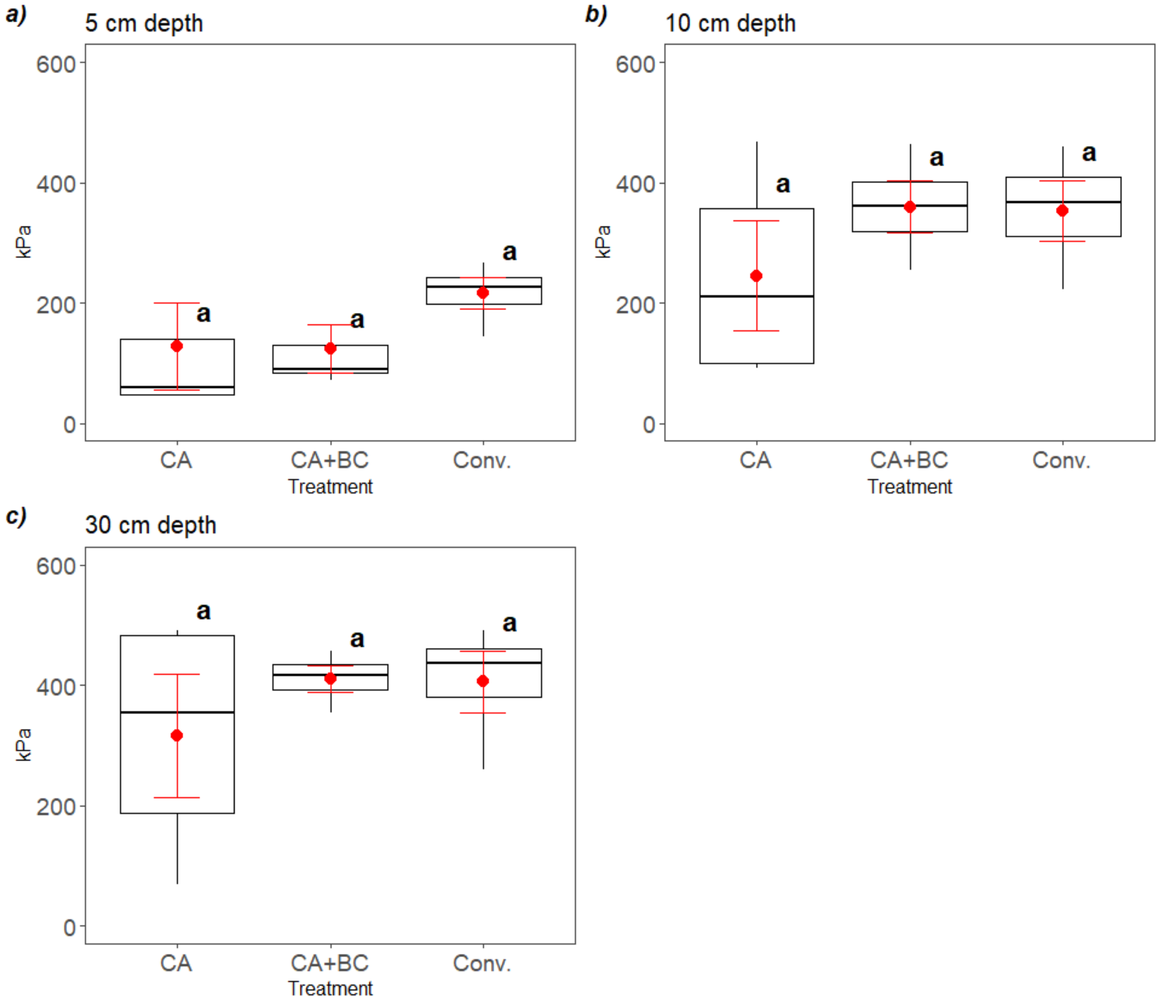


Figure 3: *Mean (± standard error) penetration resistance for; a) 5cm (n=20 each treatment); b) 10cm (n=20 each treatment); c) 30cm depth (n=20 each treatment) measured at in-depth experimental site in Alebtong (measurements conducted June 2022) over box-whisker plots (median, 25th and 75th quartile and minimum and maximum values, shown as whiskers). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05) within each depth.*

During in-field penetration resistance measurements, there was uncertainty whether the soil profile intersected the basins or not, as it was rather difficult to determine the outer edges of the basins. This uncertainty may have resulted in missing the "basin area" in the penetration resistance measurements and thus yielding a higher penetration resistance than expected. Penetration resistance was expected to be lower under CA and CA+BC treatments compared to Conv. There was a tendency of lower penetration resistance only in CA treatments which is strange considering CA+BC treatments are under the same tillage method. Nonetheless, no significant difference was observed (Figure 3). Liben et al. (2018) found a negative effect on penetration resistance in their short term (1 year) experiment compared to a positive effect in their long term (6 years). This could indicate that additional time is necessary to lower soil compaction, however, soil compaction and penetration resistance are most likely influenced by various other factors as well.

3.3.3 Infiltration

The variation of infiltration rate within treatments at both -2 cm pressure and -4 cm pressure is considerable (Figure 4). Infiltration rate for Conv. treatments show a tendency of a lower infiltration rate at -4 cm pressure compared to CA and CA+BC treatments, however no significant difference is found between any of the treatments at both pressures.

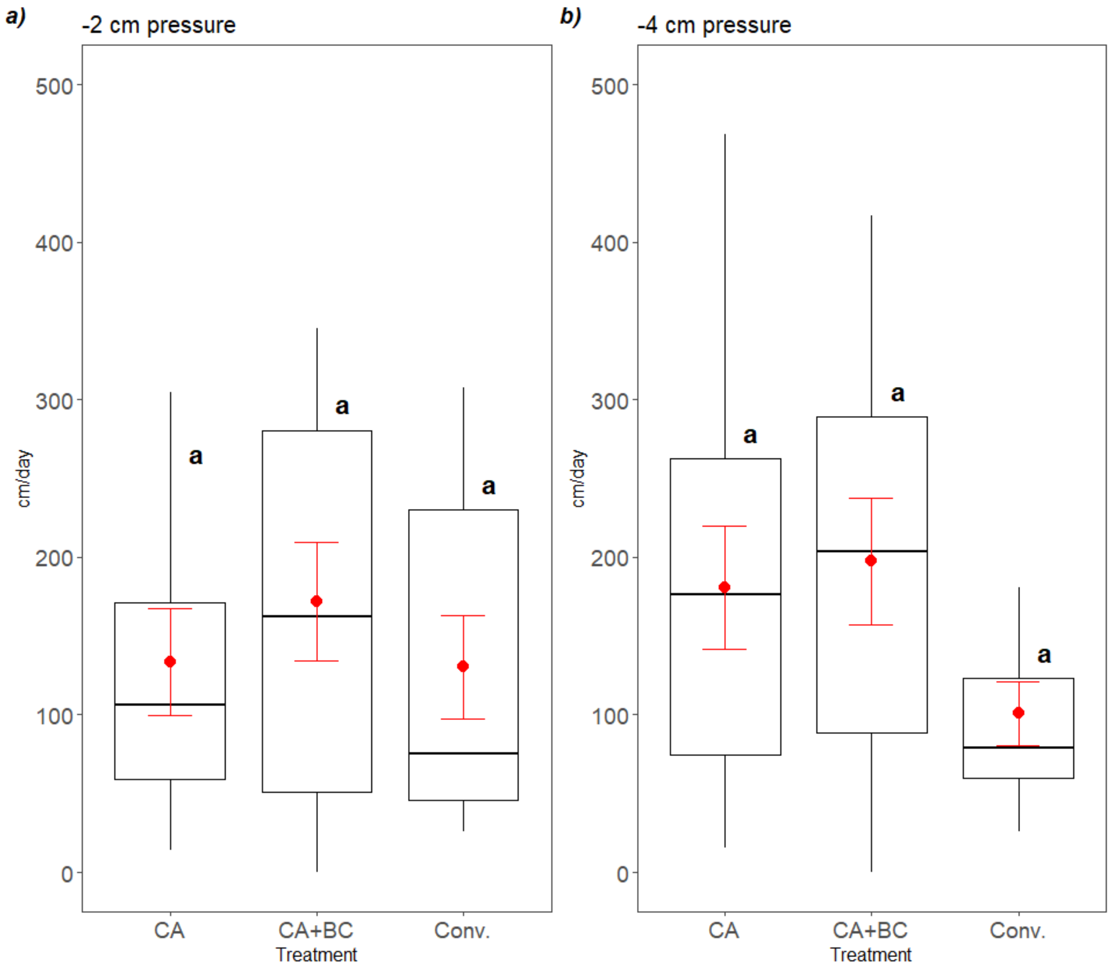


Figure 4: *Mean (± standard error) infiltration rate at: a) -2cm pressure (n=12 each treatment); b) -4 cm pressure (n=12 each treatment) measured at in-depth experimental site in Alebtong (measurements conducted June 2022) over box-whisker plots (median, 25th and 75th quartile and minimum and maximum values, shown as whiskers). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05) within each depth.*

The infiltration rate can have a great variability due to heterogeneity of the surface and large variability in soil texture and soil structure within a small area (Bentz et al., 2022). The infiltration measurements varied considerably within the treatments which may be a result of insufficient number of replicates. No significant difference was observed between treatments at both -2 cm and -4 cm pressure. However, the mean infiltration rate was slightly lower at Conv. treatments at -4cm pressure, nevertheless this tendency is vague, taking the uncertainty of the results into consideration. A in-field study by Thierfelder and Wall (2009) found similar results for a sandy soil under basin tillage, however significantly higher infiltration rates were reported in a more fine textured soil. A slightly higher infiltration rate in CA and CA+BC treatments is noticeable in the -4 cm pressure compared to the -2 cm pressure. This result is questionable as -4 cm pressure typically would deactivate a group of larger pores compared to the -2 cm pressure (Kargas et al., 2017), thus decreasing the infiltration rate. Even a single larger pore may be the reason for an unexpected difference. Such difference can be part of spatial variability of the soil itself. Using a larger number of measurements could help reduce such chances. When larger pores are excluded, the soil water should have a longer path of transport and a restricted flow, thus lowering the infiltration rate. Another explanation for the lack of any significant differences among the treatments in infiltration rate could be the relatively recent establishment of the research site. Factors such as aggregate stability, BD, and soil structure affect the infiltration rate and may take several years to develop. As the measurements were completed only 10 months after establishment it is likely that their potential impact could not be established yet. Additionally, the case of uneven distribution of BC in the basins is likely to affect the infiltration rate, although only in CA+BC treatments.

3.3.4 Soil water retention of soil collected at the in-depth trial site

There was no significant difference in water content at FC between any of the treatments (Figure 5). Water content at permanent wilting point (PWP) was significantly higher in Conv. treatments compared to CA treatments while CA+BC did not significantly differ from any of the treatments. No significant difference in PAWC was observed between the treatments. The BD was significantly higher in the Conv. treatments compared to CA+BC and CA.

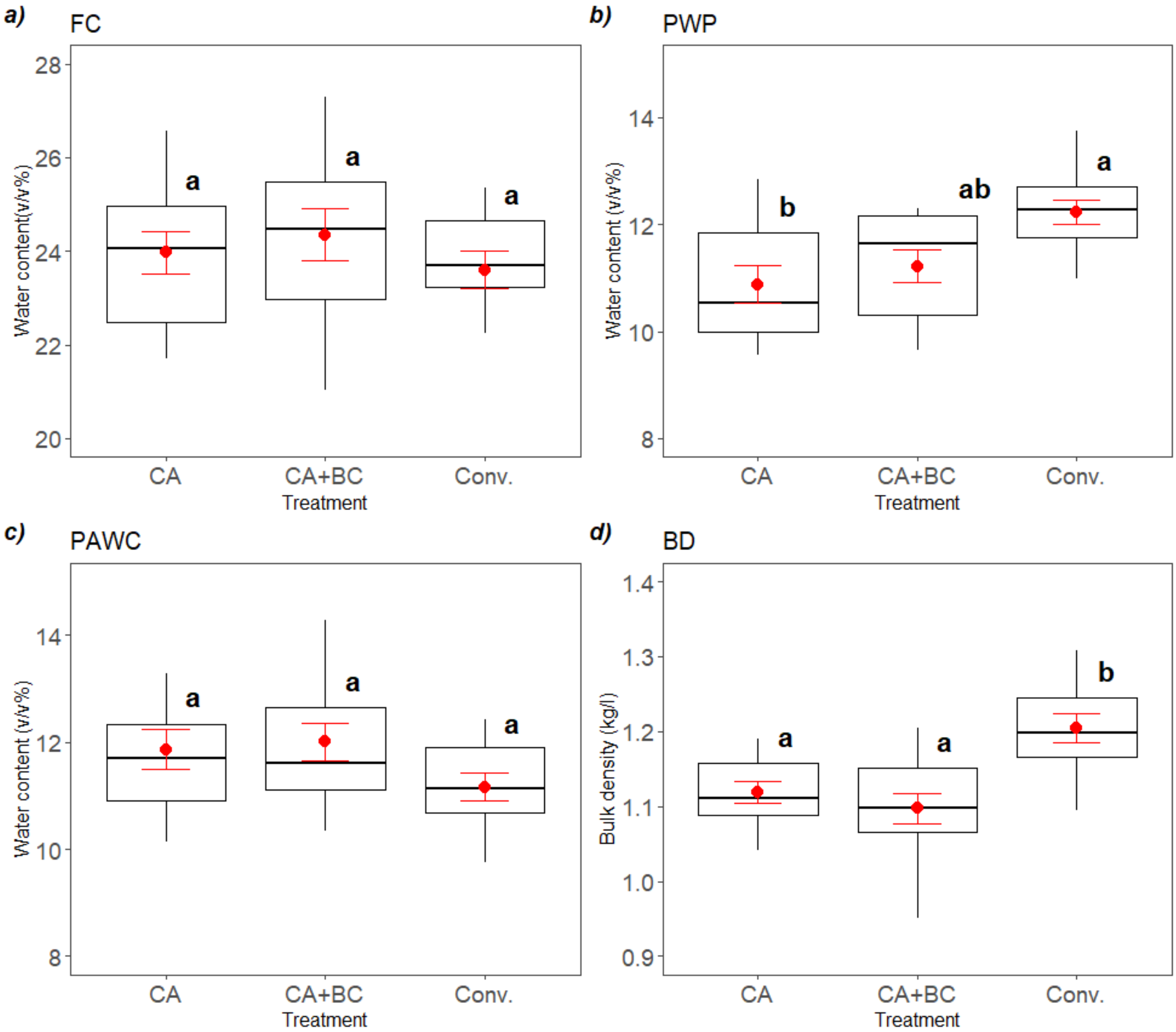


Figure 5: *Mean (± standard error) volumetric water content at a) -100cm pressure (FC) (n=12 each treatment); b) -15000cm pressure (PWP)(n=12 each treatment); c) plant available water content (PAWC)(n=12 each treatment) and d) bulk density (BD)(n=12 each treatment) from samples collected at in-depth experimental site in Alebtong (sampled June 2022) over box-whisker plots (median, 25th and 75th quartile and minimum and maximum values, shown as whiskers). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05) within each variable.*

PAWC was expected to be significantly higher in the plots under CA practice, yet no significant difference was observed on both FC and PAWC between the treatments in Figure 5. The water retention curves presented in Appendix 4 show that drainable water content was slightly higher in the treatments under CA practice. As previously described, there was most likely very little, or no BC present in the core samples collected in plots under CA+BC treatments. The positive effect of BC on water retention capabilities of BC reported by other studies (Abel et al., 2013, Obia et al., 2016) would not be detectable in these measurements, thus making the data non-representative for assessing the effect of BC on PAWC. As this was a part of the main objective in this thesis it was reasonable to establish a controlled lab experiment to investigate this further and to complement to the in-field results.

3.4 Water retention in soils with different soil/biochar mixing ratios in the lab

The lab-trial was conducted to assess the isolated effect of pigeon pea biochar (PPBC) and maize cob biochar (MCBC) on soil water retention. Both types of BC used in the experiment were readily available and made it possible to assemble artificially built samples, containing desired mixes of BC and soil. The soil used in the experiment was not agricultural soil, rather a well-drained, fine sand with low PAWC (Table 4). Upon completion of the experiment nearly all samples containing MCBC increased in water content at -15000 hPa pressure (Appendix 5) which was unexpected. This increase in water content influenced the results when calculating PAWC. A possible reason for this is that the saturation time for the subsamples used in the -15000 hPa measurements was allowed to saturate for 7 days (opposed to 3 days for samples measured between saturation and -3000 hPa). It is possible that 7 days of saturation time allowed for more water to be absorbed by the BC, in combination with a strong water retention at -15000 hPa. Additionally, 100 % BC dosages for PWP measurements were allowed to saturate for a period of three weeks on a shaker table.

3.4.1 Biochar hydrophobicity

Neither fractions of PPBC were water repellent. Maize cob biochar, however, was extremely water repellent for the <2 mm fraction and severely water repellent in the powdered fraction.

Table 3: *Water droplet penetration time for pigeon pea biochar (PPBC), powdered pigeon pea biochar (PPBCP), maize cob biochar (MCBCP), powdered maize cob biochar (MCBCP). Hydrophobicity is classified by: wettable=< 5 s; lightly water repellent = 5–60 s; strongly water repellent = 60–600 s; severely water repellent = 600–3600 s; extremely water repellent = > 1 h (Dekker and Jungerius, 1990).*

PPBC	PPBCP	MCBC	MCBCP
< 5 seconds	<5 seconds	>1 hour	1020 seconds

3.4.2 Comparing two biochar types and their effect on soil water retention

Pigeon pea biochar had significantly higher PAWC (7.1 %) compared to the MCBC (3.2 %) and Control (3.36 %) (Figure 6). Maize cob biochar did have a significantly higher water content at FC compared to the Control, yet it also held significantly more water at PWP. The elevated water content at PWP caused the PAWC in MCBC to be lower than the Control, however not significantly. Bulk density was significantly lowered in the samples containing BC in the order of PPBC<MCBC<Control, which corresponds with the BD of 100 % BC seen in Table 4.

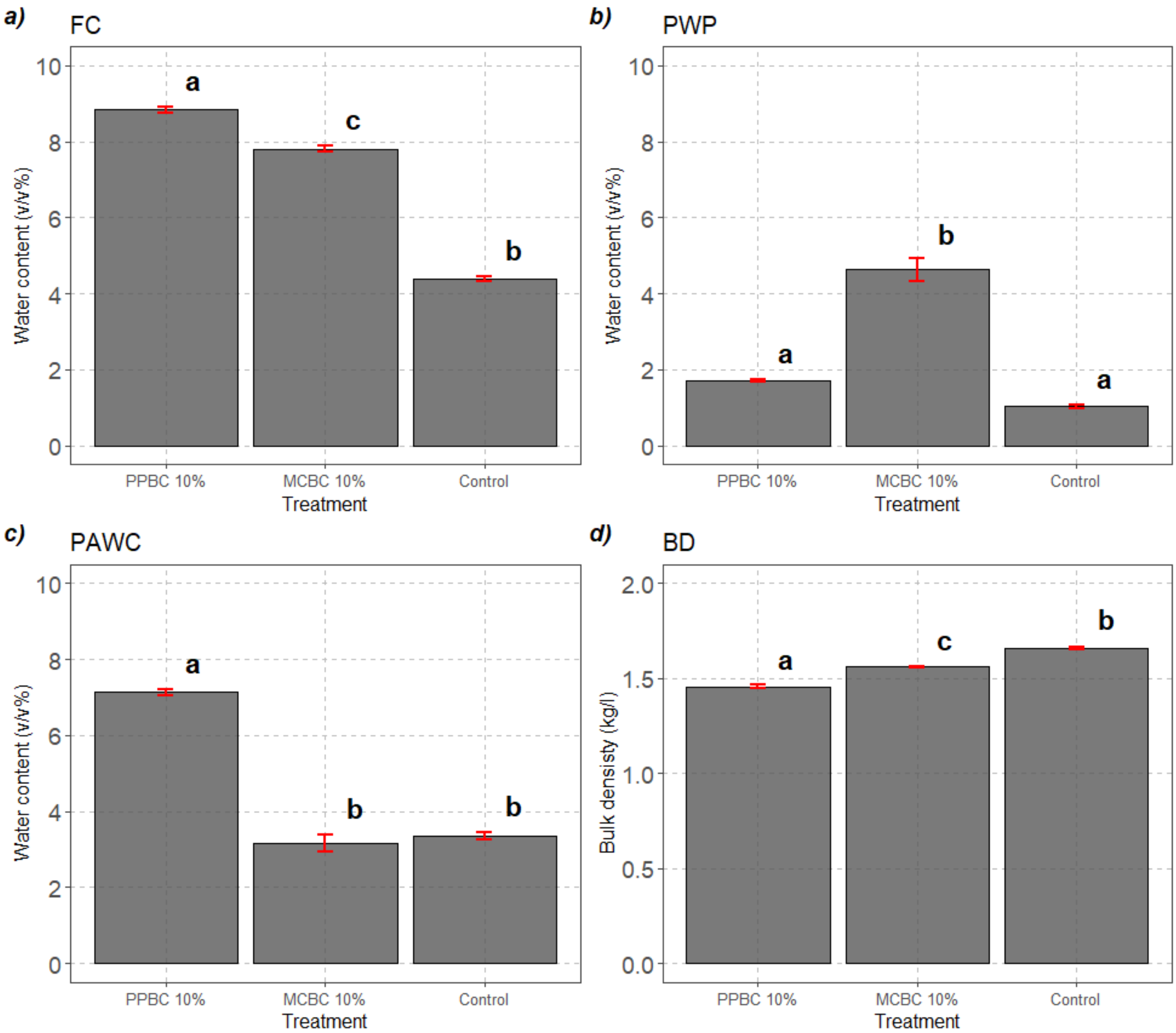


***Figure 6**: Mean (± standard error) volumetric water content at **a)** -100cm pressure (FC) (n=3 each treatment); **b)** -15000cm pressure (PWP)(n=3 each treatment); **c)** plant available water content (PAWC)(n=3 each treatment); **d)** bulk density (BD)(n=3 each treatment) visualized in bar-plots. Assessing difference in water content between biochar type for >2 mm particle size, pigeon pea biochar (PPBC); <2 mm particle size, maize cob biochar (MCBC) and >2 mm particle size, sand (Control) in artificially build samples. Samples contain 10 % biochar, by volume. Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05).*

There was almost a double and significantly higher PAWC in PPBC compared to both MCBC and Control in Figure 6. The 10 % PPBC dosage is close to the BC dosage that was supposed to be added in the field trial (approximately 9 %) and could give an indication on how PAWC would have been affected by the BC, in-field. Maize cob biochar did not significantly increase PAWC under lab conditions. As previously mentioned, it may be due to a change in method when determining PWP and the strong water repellency of MCBC (Table 3). Yet, similar results are reported by Martinsen et al. (2014) where 10 % MCBC by volume was added to 3 different sandy soils, in the lab. The lab trial found no significant difference in PAWC between the BC and soil in 2 out of 3 soils included. Obia et al. (2016) found however, MCBC to increased PAWC by 3 % for each percent BC added, under field conditions in a sandy loam in Zambia. These confounding results demonstrate that various factors likely influence the ability of MCBC to improve soil water retention. The relatively short time span of our experiment may be the reason for low PAWC, and it is possible that the water retention potential of MCBC could increase over time. The ability of BC to lower soil BD is apparent for both PPBC and MCBC. An increase in soil BD and improved soil porosity is previously reported by several other studies (Busscher et al., 2010, Lei and Zhang, 2013, Obia et al., 2016). In this experiment it illustrates the direct effect BC asserts on soil BD which corresponds with the initial BD of the BC itself. The BD of the PPBC (0.19) is lower compared to the MCBC (0.30), thus implying a higher porosity in the PPBC compared to the MCBC. Which then again possibly allows for higher water storage in PPBC. Based on our results, pigeon pea biochar seems more beneficial than MCBC as a soil amendment to improve soil water retention. These results could assist in promoting pigeon pea as a viable BC feedstock.

3.4.3 Does soil water retention differ between different biochar size fractions?

The difference at FC with 2 % BC dosage was not significant between any of the treatments (Figure 7). Maize cob biochar contained most water at PWP and was significantly higher than all the other treatments. The lowest water content at PWP was found in PPBCP which was significantly lower than the control by ~0.4 %. The PAWC did not show any significant difference between all treatments. The BD was significantly higher in the control compared to the other treatments where PPBC had the biggest effect on BD. This shows that even low doses of BC can alter BD.

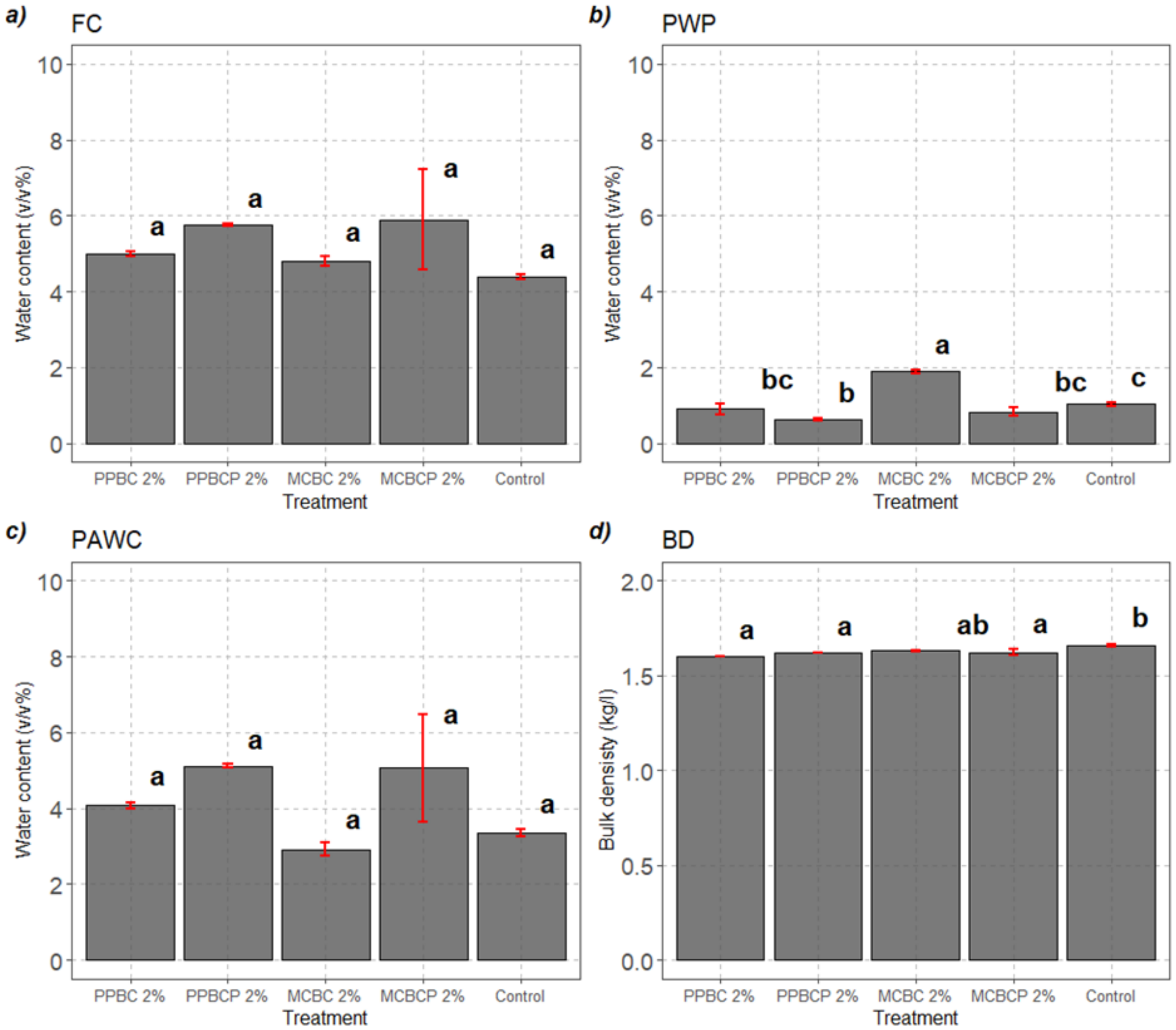


***Figure 7**: Mean (± standard error) volumetric water content at **a)** -100cm pressure (FC) (n=3 each treatment except for MCBCP where n=2); **b)** -15000cm pressure (PWP)(n=3 each treatment except for MCBCP where n=2); **c)** plant available water content (PAWC)(n=3 each treatment except for MCBCP where n=2); **d)** bulk density (BD)(n=3 each treatment except for MCBCP where n=2) visualized in bar-plots. Assessing difference in water content between biochar type and particle size for >2 mm particle size, pigeon pea biochar (PPBC); powdered pigeon pea biochar (PPBCP); <2 mm particle size, maize cob biochar (MCBC); powdered maize cob biochar (MCBCP) and >2 mm particle size, sand (Control) in artificially build samples. All samples contain 2 % biochar, by volume. Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05).*

The difference in PAWC between <2mm size fraction and powdered BC was not significant. The lack of significant difference is most likely due to an outlier in the MCBC 2% treatment (Table 4), strongly influencing the statistical test. Yet a higher PAWC is noticeable in the powdered BC treatments compared to the courser particle sizes, for both BC types. This suggests that the fine particle BC improves water retention. This is supported by Alghamdi et al. (2020) who conducted a greenhouse experiment where 2.0-1.0 mm, 1.0-0.5 mm, 0.5- 0.1 mm and <0.1 mm of Date palm BC, at an application rate of 4 % by volume, was applied to a sandy loam. They found the greatest increase in PAWC to be in treatments receiving the <0.1 mm BC fraction. The low PAWC in MCBC is also a result of the increase in water content at PWP thus yielding an unlikely low PAWC.

3.4.4 Soil water retention affected by biochar dosage

The 2 % PPBC dosage showed no significant difference in volumetric PAWC compared to the control, however at 5 % PPBC dosage and above there was a significantly higher PAWC compared to the control. At 100 % BC dosage the FC was over 50 % (Table 4), showing that the PPBC alone holds the ability to store half of its volume at FC and release most of it at PWP. The volumetric PAWC in MCBC was lower than the control in 2 %, 5 %, 10 % and 50 % dosages where only the 100 % BC dosage was significantly higher.

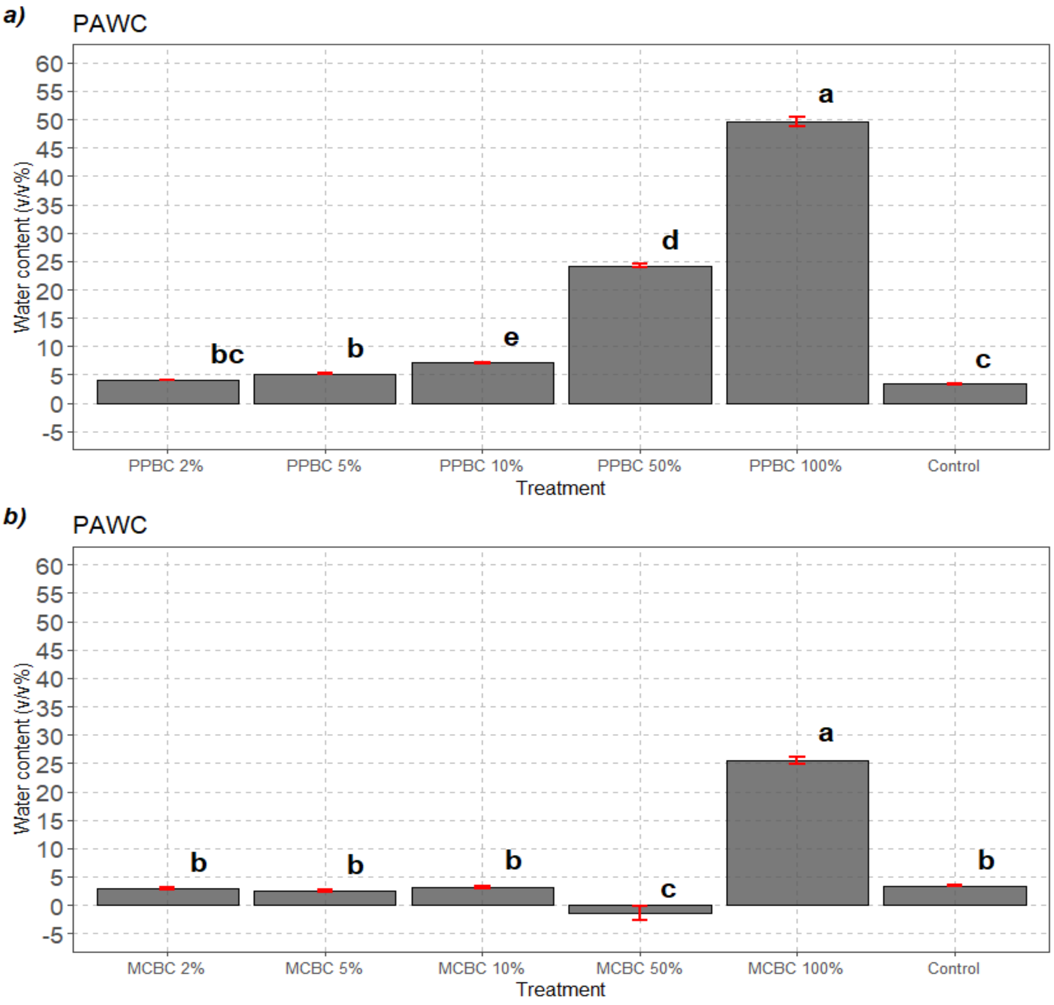


Figure 8: *Mean (± standard error) volumetric plant available water content (PAWC)(n=3 each treatment) visualized in bar-plots. Assessing difference in water content between biochar dosage for* ***a)*** *>2 mm particle size, pigeon pea biochar (PPBC);* ***b)*** *<2 mm particle size, maize cob biochar (MCBC) in artificially build samples. Samples contain 2 %, 5%, 10 %, 50 % and 100 % biochar, by volume. Anomaly in the data at MCBC 50 %. Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05).*

The results show that PAWC is dependent on biochar type (Figure 8). Increasing dosage of pigeon pea biochar consistently increased PAWC, while MCBC reduced the PAWC in dosages from 2 % to 50 %. The increase observed in PPBC treatments may be due to a high porosity of the biochar. The MCBC most likely has a less porous structure and different chemical composition. Additionally, the MCBC is also more water repellent than the PPBC (Table 3).

The samples containing MCBC are all below the control in PAWC except for the 100 % dosage (Table 4). At 50 % BC dosage there is an anomaly in the data where the PAWC in the samples are showing a negative value. The negative value is a result of higher water content at PWP (Appendix 5).

***Table 4**: Mean volumetric water content and standard error for all treatments among artificially build soil samples at -100cm pressure (FC) (n=3 each treatment); -15000cm pressure (PWP)(n=3 each treatment); plant available water content (PAWC)(n=3 each treatment); bulk density (BD)(n=3 each treatment).*

Treatment	Amount BC (v/v)	**FC**	std.err	**PWP**	std.err	**PAWC**	std.err	**BD**	std.err
Control	0 %	**4.4**	0.05	**1.03**	0.04	**3.36**	0.091	**1.66**	0.008
PPBC	2 %	**5.0**	0.07	**0.9**	0.14	**4.1**	0.079	**1.60**	0.001
	5 %	**6.2**	0.14	**1.0**	0.07	**5.2**	0.070	**1.57**	0.004
	10 %	**8.8**	0.07	**1.7**	0.03	**7.1**	0.027	**1.46**	0.007
	50 %	**28.3**	0.27	**4.1**	0.06	**24.2**	0.058	**0.98**	0.003
	100 %	**53.1**	0.76	**3.5**	0.14	**49.6**	0.139	**0.19**	0.001
MCBC	2 %	**4.8**	0.13	**1.9**	0.04	**2.9**	0.045	**1.63**	0.001
	5 %	**5.8**	0.02	**3.4**	0.16	**2.5**	0.164	**1.60**	0.010
	10 %	**7.8**	0.08	**4.6**	0.30	**3.2**	0.299	**1.56**	0.004
	50 %	**21.5**	0.67	**24.6**	1.36	**-3.1**	1.365	**1.06**	0.026
	100 %	**38.3**	0.63	**12.8**	1.06	**25.5**	1.060	**0.30**	0.001
PPBCP	2 %	**5.7**	0.03	**0.6**	0.02	**5.1**	0.023	**1.62**	0.001
	50 %	**26.9**	0.42	**2.3**	0.12	**24.5**	0.116	**1.12**	0.002
MCBCP	2 %	**5.9**	1.31	**0.8**	0.11	**5.1**	0.112	**1.62**	0.014
	50 %	**32.2**	0.36	**3.0**	0.17	**29.2**	0.173	**1.20**	0.002

4 Conclusion

Based on our field-trial, Conservation agriculture without the addition of BC significantly decreased BD and water content at PWP. CA with the addition of BC decreased BD, yet it had no significant influence on the other physical soil properties including PAWC. The missing effect of BC is most likely explained by the incorrect application of BC to the basins at the in-depth trial site. In the controlled lab trial, PPBC greatly improved water retention under a 10 % dosage, which is considered a realistic application rate for small-holder farmers. No effect of MCBC on PAWC was found in this study, though some uncertainty exists in the results based on the increase in water content at PWP. The inconsistent saturation of the samples is likely to have influenced the results. However, the same methodology was applied to both biochar types, making both types of BC directly comparable to each other, within this study. Smaller biochar particle sizes tended to increase PAWC of the soil for both types of biochar examined in the lab study, yet no significant difference was observed.

Plant available water content of PPBC significantly increased for each dosage in the order of 5%<10%<50%<100% compared to the control, except for the 2% dosage. For the maize cob biochar however, the trend was not the same and resulted in only a significant increase of PAWC at 100 % dosage.

In conclusion, our results suggest that biochar has a positive impact on soil water retention, however it depends on biochar type, particle size and external variables e.g. soil type, climate and weather.

5 References

ABEL, S., PETERS, A., TRINKS, S., SCHONSKY, H., FACKLAM, M. & WESSOLEK, G. 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma,* 202**,** 183-191.

ABROL, V., BEN-HUR, M., VERHEIJEN, F. G., KEIZER, J. J., MARTINS, M. A., TENAW, H., TCHEHANSKY, L. & GRABER, E. R. 2016. Biochar effects on soil water infiltration and erosion under seal formation conditions: rainfall simulation experiment. *Journal of Soils and Sediments,* 16**,** 2709-2719.

AKWANGO, D., OBAA, B. B., TURYAHABWE, N., BAGUMA, Y. & EGERU, A. 2017. Effect of drought early warning system on household food security in Karamoja subregion, Uganda. *Agriculture & Food Security,* 6**,** 1-12.

ALGHAMDI, A. G., ALKHASHA, A. & IBRAHIM, H. M. 2020. Effect of biochar particle size on water retention and availability in a sandy loam soil. *Journal of Saudi Chemical Society,* 24**,** 1042-1050.

ALHASSOUN, R. 2011. Studies on factors affecting the infiltration capacity of agricultural soils. *Dissertationen aus dem Julius Kühn-Institut*.

ALLER, D., RATHKE, S., LAIRD, D., CRUSE, R. & HATFIELD, J. 2017. Impacts of fresh and aged biochars on plant available water and water use efficiency. *Geoderma,* 307**,** 114-121.

ANDERSON, R., BAYER, P. E. & EDWARDS, D. 2020. Climate change and the need for agricultural adaptation. *Current opinion in plant biology,* 56**,** 197-202.

BASHAGALUKE, J. B., LOGAH, V., OPOKU, A., SARKODIE-ADDO, J. & QUANSAH, C. 2018. Soil nutrient loss through erosion: Impact of different cropping systems and soil amendments in Ghana. *PloS one,* 13**,** e0208250.

BENTZ, J., PATEL, R. A., BENARD, P., LIEU, A., HAUPENTHAL, A. & KROENER, E. 2022. How heterogeneous pore scale distributions of wettability affect infiltration into porous media. *Water,* 14**,** 1110.

BLANCO-CANQUI, H. 2017. Biochar and soil physical properties. *Soil Science Society of America Journal,* 81**,** 687-711.

BORRELLI, P., ROBINSON, D. A., PANAGOS, P., LUGATO, E., YANG, J. E., ALEWELL, C., WUEPPER, D., MONTANARELLA, L. & BALLABIO, C. 2020. Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences,* 117**,** 21994-22001.

BREMNER, J. & MULVANEY, C. 1982. Nitrogen—Total 1 In Page AL (Ed.), Methods of Soil Analysis Part 2 Chemical and Microbiological Properties. Agronomy Monograph (pp. 595–624). Madison, WI: American Society of Agronomy. *Soil Science Society of America.[Google Scholar]*.

BROWN, R. C. & WANG, K. 2017. *Fast Pyrolysis of Biomass: Advances in Science and Technology*, Royal Society of Chemistry.

BUSSCHER, W. J., NOVAK, J. M., EVANS, D. E., WATTS, D. W., NIANDOU, M. & AHMEDNA, M. 2010. Influence of pecan biochar on physical properties of a Norfolk loamy sand. *Soil Science,* 175**,** 10-14.

CAIRNS, J. E., HELLIN, J., SONDER, K., ARAUS, J. L., MACROBERT, J. F., THIERFELDER, C. & PRASANNA, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security,* 5**,** 345-360.

CORBEELS, M., NAUDIN, K., WHITBREAD, A. M., KüHNE, R. & LETOURMY, P. 2020. Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa. *Nature Food,* 1**,** 447-454.

CORNELISSEN, G., MARTINSEN, V., SHITUMBANUMA, V., ALLING, V., BREEDVELD, G. D., RUTHERFORD, D. W., SPARREVIK, M., HALE, S. E., OBIA, A. & MULDER, J. 2013. Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. *Agronomy,* 3**,** 256-274.

CORNELISSEN, G., PANDIT, N. R., TAYLOR, P., PANDIT, B. H., SPARREVIK, M. & SCHMIDT, H. P. 2016. Emissions and char quality of flame-curtain" Kon Tiki" Kilns for Farmer-Scale charcoal/biochar production. *PloS one,* 11**,** e0154617.

DEKKER, L. & JUNGERIUS, P. 1990. Water repellency in the dunes with special reference to the Netherlands. *Catena, Supplement***,** 173-183.

DEMISIE, W., LIU, Z. & ZHANG, M. 2014. Effect of biochar on carbon fractions and enzyme activity of red soil. *Catena,* 121**,** 214-221.

DOERR, S. H., SHAKESBY, R. & WALSH, R. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews,* 51**,** 33-65.

EGNéR, H., RIEHM, H. & DOMINGO, W. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. *Chemische Extraktionsmethoden zur Phosphor-und Kaliumbestimmung. Kungliga Lantbrukshögskolans Annaler,* 26**,** 199-215.

FAO. 2022. Available: https://www.fao.org/conservation-agriculture/en/ [Accessed 22.04 2022].

FAROOQ, M. & SIDDIQUE, K. H. 2015. Conservation agriculture: concepts, brief history, and impacts on agricultural systems. *Conservation agriculture.* Springer.

FRAVAL, S., OOSTING, S., DE BOER, I., LANNERSTAD, M. & VAN WIJK, M. Food security in rural sub-Saharan Africa: a household level assessment. WIAS Science Day 2019: Trade-Offs in Science, 2019. Wageningen University & Research, 14-14.

GAO, S., DELUCA, T. H. & CLEVELAND, C. C. 2019. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of the Total Environment,* 654**,** 463-472.

GHANI, A., DEXTER, M. & PERROTT, K. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil biology and biochemistry,* 35**,** 1231-1243.

GHOLAMAHMADI, B., JEFFERY, S., GONZALEZ-PELAYO, O., PRATS, S. A., BASTOS, A. C., KEIZER, J. J. & VERHEIJEN, F. G. 2023. Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis. *Science of The Total Environment,* 871**,** 161860.

GILLER, K. E., WITTER, E., CORBEELS, M. & TITTONELL, P. 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field crops research,* 114**,** 23-34.

GOWING, J. & PALMER, M. 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. *Soil use and management,* 24**,** 92-99.

HAGHNAZARI, F., SHAHGHOLI, H. & FEIZI, M. 2015. Factors affecting the infiltration of agricultural soils. *International Journal of Agronomy and Agricultural Research,* 6**,** 21-35.

HAO, X., BALL, B., CULLEY, J., CARTER, M. & PARKIN, G. 2008. Soil density and porosity. *Soil sampling and methods of analysis,* 2**,** 179-196.

ISABIRYE, M., MWESIGE, D., SSALI, H., MAGUNDA, M. & LWASA, J. 2004. Soil resource information and linkages to agricultural production. *Uganda Journal of Agricultural Sciences,* 9**,** 215-221.

JAGGER, P. & KITTNER, N. 2017. Deforestation and biomass fuel dynamics in Uganda. *Biomass and Bioenergy,* 105**,** 1-9.

KABAMBA, H. & MUIMBA-KANKOLONGO, A. 2009. Adoption and impact of conservation farming on crop productivity among smallholder farmers in Kapiri Mposhi District of Zambia. *Journal of Animal & Plant Sciences,* 3**,** 205-214.

KARGAS, G., LONDRA, P. & VALIANTZAS, J. 2017. Estimation of near-saturated hydraulic conductivity values using a mini disc infiltrometer. *Water Utility Journal,* 16**,** 97-104.

KAWEESA, S. H., NDAH, H. T., SCHULER, J., MELCHER, A. & LOISKANDL, W. 2020. Understanding the conditions of conservation agriculture adoption in Lango region, Uganda. *Agroecology and Sustainable Food Systems,* 44**,** 1260-1279.

KHADEMALRASOUL, A., NAVEED, M., HECKRATH, G., KUMARI, K., DE JONGE, L. W., ELSGAARD, L., VOGEL, H.-J. & IVERSEN, B. V. 2014. Biochar effects on soil aggregate properties under no-till maize. *Soil Science,* 179**,** 273-283.

KLUTE, A. 1986. Water retention: laboratory methods. *Methods of soil analysis: part 1 physical and mineralogical methods,* 5**,** 635-662.

KVæRNø, H. S. 2023. Mualem van Genuchten curve visualization.

LEHMANN, J., COWIE, A., MASIELLO, C. A., KAMMANN, C., WOOLF, D., AMONETTE, J. E., CAYUELA, M. L., CAMPS-ARBESTAIN, M. & WHITMAN, T. 2021. Biochar in climate change mitigation. *Nature Geoscience,* 14**,** 883-892.

LEI, O. & ZHANG, R. 2013. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. *Journal of Soils and Sediments,* 13**,** 1561-1572.

LETEY, J., CARRILLO, M. & PANG, X. 2000. Approaches to characterize the degree of water repellency. *Journal of Hydrology,* 231**,** 61-65.

LIBEN, F., TADESSE, B., TOLA, Y., WORTMANN, C., KIM, H. & MUPANGWA, W. 2018. Conservation agriculture effects on crop productivity and soil properties in Ethiopia. *Agronomy Journal,* 110**,** 758-767.

LIU, Z., DUGAN, B., MASIELLO, C. A. & GONNERMANN, H. M. 2017. Biochar particle size, shape, and porosity act together to influence soil water properties. *Plos one,* 12**,** e0179079.

MALHI, G. S., KAUR, M. & KAUSHIK, P. 2021. Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability,* 13**,** 1318.

MARTINSEN, V., ALLING, V., NURIDA, N., MULDER, J., HALE, S., RITZ, C., RUTHERFORD, D., HEIKENS, A., BREEDVELD, G. D. & CORNELISSEN, G. 2015. pH effects of the addition of three biochars to acidic Indonesian mineral soils. *Soil Science and Plant Nutrition,* 61**,** 821-834.

MARTINSEN, V., MULDER, J., SHITUMBANUMA, V., SPARREVIK, M., BøRRESEN, T. & CORNELISSEN, G. 2014. Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science,* 177**,** 681-695.

METER GROUP. 2021. *Mini Disk Manual Web* [Online]. Available: https://publications.metergroup.com/Manuals/20421_Mini_Disk_Manual_Web.pdf [Accessed 21.12 2022].

MUBIRU, D. N., KOMUTUNGA, E., AGONA, A., APOK, A. & NGARA, T. 2012. Characterising agrometeorological climate risks and uncertainties: Crop production in Uganda. *South African Journal of Science,* 108**,** 1-11.

MUNERA-ECHEVERRI, J., MARTINSEN, V., DöRSCH, P., OBIA, A. & MULDER, J. 2022. Pigeon pea biochar addition in tropical Arenosol under maize increases gross nitrification rate without an effect on nitrous oxide emission. *Plant and Soil,* 474**,** 195-212.

MøBERG, J. & PETERSEN, L. 1982. Øvelsesveiledning til geologi og jordbundlære: Part 2. *Den Kongelige Veterinære og Landbohøyskole, Copenhagen, Denmark*.

NELSON, D. A. & SOMMERS, L. E. 1983. Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 2 chemical and microbiological properties,* 9**,** 539-579.

NSUBUGA, F. W. & RAUTENBACH, H. 2018. Climate change and variability: a review of what is known and ought to be known for Uganda. *International Journal of Climate Change Strategies and Management*.

OBIA, A., BøRRESEN, T., MARTINSEN, V., CORNELISSEN, G. & MULDER, J. 2017. Effect of biochar on crust formation, penetration resistance and hydraulic properties of two coarse-textured tropical soils. *Soil and Tillage Research,* 170**,** 114-121.

OBIA, A., MULDER, J., MARTINSEN, V., CORNELISSEN, G. & BøRRESEN, T. 2016. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research,* 155**,** 35-44.

OPENAI. 2023. *ChatGPT (GPT-3.5, large language model)* [Online]. Available: https://chat.openai.com/ [Accessed].

OUYANG, L., WANG, F., TANG, J., YU, L. & ZHANG, R. 2013. Effects of biochar amendment on soil aggregates and hydraulic properties. *Journal of soil science and plant nutrition,* 13**,** 991-1002.

PALM, C., BLANCO-CANQUI, H., DECLERCK, F., GATERE, L. & GRACE, P. 2014. Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment,* 187**,** 87-105.

PARFITT, R. 1989. Optimum conditions for extraction of Al, Fe, and Si from soils with acid oxalate. *Communications in Soil Science and Plant Analysis,* 20**,** 801-816.

QGIS DEVELOPMENT TEAM 2022. QGIS 3.22.6 Geographic Information System. QGIS Association.

R DEVELOPMENT CORE TEAM 2022. A language and environment for statistical computing.: R Foundation for Statistical Computing, Vienna, Austria.

ROOBROECK, D., HOOD-NOWOTNY, R., NAKUBULWA, D., TUMUHAIRWE, J. B., MWANJALOLO, M. J. G., NDAWULA, I. & VANLAUWE, B. 2019. Biophysical potential of crop residues for biochar carbon sequestration, and co-benefits, in Uganda. *Ecological Applications,* 29**,** e01984.

SAHOO, S. S., VIJAY, V. K., CHANDRA, R. & KUMAR, H. 2021. Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo. *Cleaner engineering and technology,* 3**,** 100101.

SCHMIDT, H. P., TAYLOR, P., EGLISE, A. & ARBAZ, C. 2014. Kon-Tiki flame curtain pyrolysis for the democratization of biochar production. *Biochar J,* 1**,** 14-24.

SCHOLLENBERGER, C. & SIMON, R. 1945. Determination of exchange capacity and exchangeable bases in soil—ammonium acetate method. *Soil science,* 59**,** 13-24.

SPARREVIK, M., FIELD, J. L., MARTINSEN, V., BREEDVELD, G. D. & CORNELISSEN, G. 2013. Life cycle assessment to evaluate the environmental impact of biochar implementation in conservation agriculture in Zambia. *Environmental science & technology,* 47**,** 1206-1215.

STOTT, P. 2016. How climate change affects extreme weather events. *Science,* 352**,** 1517-1518.

TAYLOR, M. 2018. Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies,* 45**,** 89-107.

THIERFELDER, C., BAUDRON, F., SETIMELA, P., NYAGUMBO, I., MUPANGWA, W., MHLANGA, B., LEE, N. & GéRARD, B. 2018. Complementary practices supporting conservation agriculture in southern Africa. A review. *Agronomy for Sustainable Development,* 38**,** 1-22.

THIERFELDER, C. & WALL, P. C. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and tillage research,* 105**,** 217-227.

VAN GENUCHTEN, M. V., LEIJ, F. & YATES, S. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils.

VEIHMEYER, F. & HENDRICKSON, A. 1949. Methods of measuring field capacity and permanent wilting percentage of soils. *Soil science,* 68**,** 75-94.

WICKHAM, H. 2016. ggplot2: Elegant Graphics for Data Analysis.: Springer-Verlag New York.

WOLKA, K., BIAZIN, B., MARTINSEN, V. & MULDER, J. 2021. Soil and water conservation management on hill slopes in Southwest Ethiopia. I. Effects of soil bunds on surface runoff, erosion and loss of nutrients. *Science of The Total Environment,* 757**,** 142877.

WORLDBANKGROUP. 2022. Available: https://climateknowledgeportal.worldbank.org/country/uganda/climate-data-historical [Accessed 20.12 2022].

YI, L., XIN, R., ROBERT, H., MALONE, R. & YING, Z. 2018. Characteristics of water infiltration in layered water-repellent soils. *Pedosphere,* 28**,** 775-792.

YORK, C. 1993. A questionnaire survey of dry patch on golf courses in the United Kingdom. *Journal of the Sports Turf Research Institute,* 69**,** 20-30.

ZHANG, J., AMONETTE, J. E. & FLURY, M. 2021. Effect of biochar and biochar particle size on plant-available water of sand, silt loam, and clay soil. *Soil and Tillage Research,* 212**,** 104992.

6 Appendix

Appendix 1: *Mean concentration of extractable Fe and AL (Mn and P) by ammonium oxalate from in-depth experimental site in Alebtong (sampled June 2022) where ± corresponds to standard error (n=4 each treatment). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.) Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05). n = 4 for each treatment.*

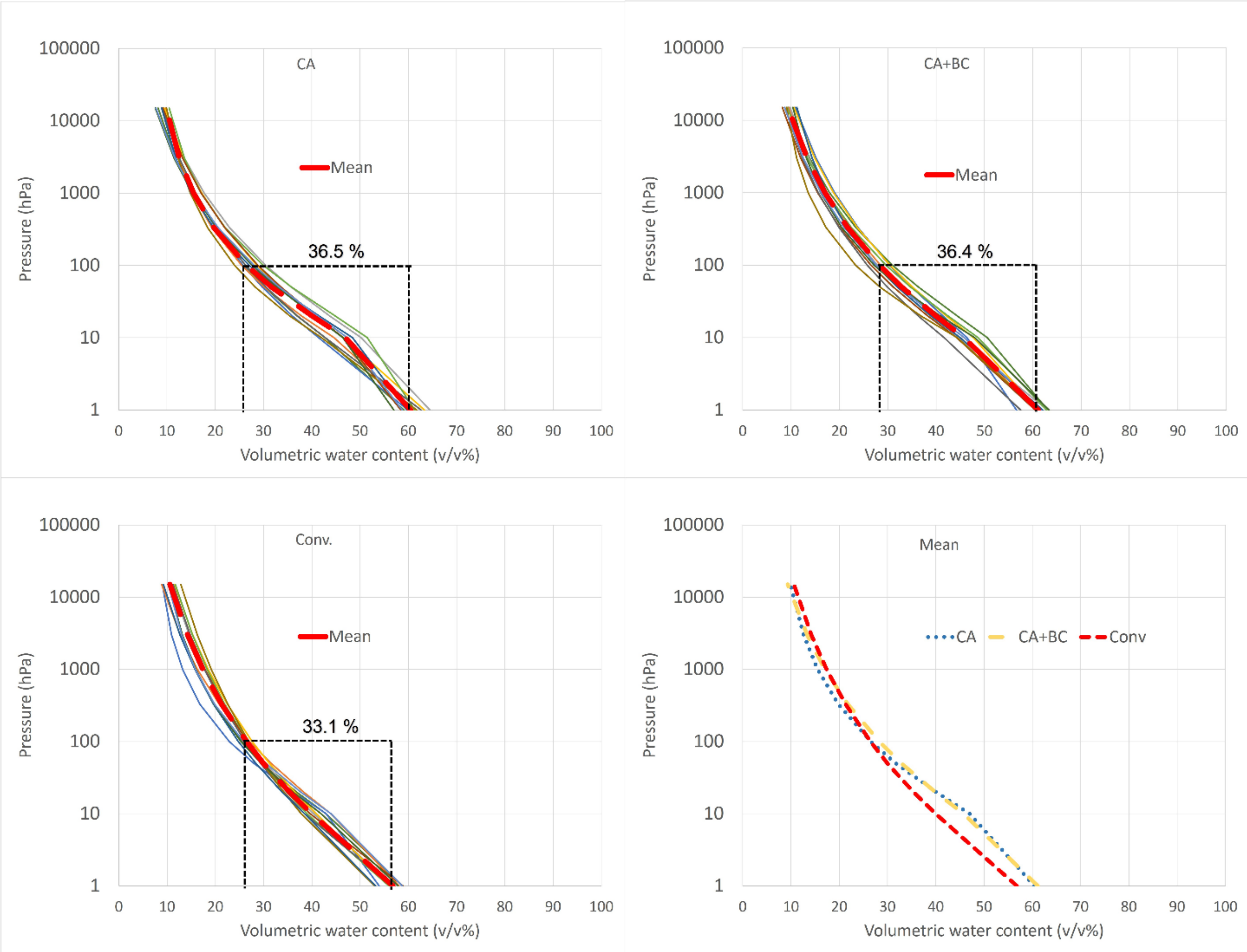
Treatment	CA	CA+BC	Conv.
Al (g/kg)	1.80±0.37 [a]	1.50±0.09 [a]	1.23±0.05 [a]
Fe (g/kg)	1.73±0.10 [a]	1.65±0.06 [a]	1.68±0.08 [a]
Mn (g/kg)	0.39±0.02 [a]	0.42±0.02 [a]	0.45±0.03 [a]
P (g/kg)	0.27±0.04 [a]	0.28±0.04 [a]	0.30±0.06 [a]

Appendix 2: *Mean concentration of extractable elements by ammonium lactate from samples collected at in-depth experimental site in Alebtong (sampled June 2022) where ± corresponds to standard error (n=4 each treatment). The treatments include conservation agriculture (CA), conservation agriculture + addition of biochar (CA+BC) and conventional practice (Conv.). Letters correspond to significant difference between treatments (Tukey HSD, p-value <0.05). n = 4 for each treatment.*

Treatment	CA	CA+BC	Conv.
Al (mg/kg)	172.5±36.8 [a]	155±6.5 [a]	125±6.5 [a]
Ca (mg/kg)	2025±278.0 [a]	2075±449.8 [a]	1775±352.1 [a]
Co (µg/kg)	1775±165.2 [a]	2125±221.3 [a]	2050±263.0 [a]
Fe (mg/kg)	190±43.6 [a]	182.5±22.5 [a]	170±22.7 [a]
K (mg/kg)	535±95.4 [a]	495±40.3 [a]	515±52.5 [a]
Mg (mg/kg)	215±9.6 [a]	207.5±14.9 [a]	200±16.3 [a]
Mn (mg/kg)	137.5±10.3 [a]	152.5±16.0 [a]	152.5±23.6 [a]
Na (mg/kg)	14.5±1.6 [a]	11.7±0.7 [a]	14.75±2.2 [a]
P (mg/kg)	86±16.4 [a]	97.5±31.5 [a]	99±41.3 [a]
Zn (mg/kg)	6.1±1.0 [a]	6.4±1.2 [a]	14.9±8.4 [a]

Appendix 3: *Results from soil pF. Volumetric water content of each sample.*

Plot	Treatment	Saturation	Sandbox				Pressure chamber				
			-10 hPa	-20 hPA	-50 hPA	-100 hPa	-100 hPa	-330 hPa	-1000 hPa	-3000 hPa	-15000 hPa
1	CA	59.0	42.4	40.7	29.7	27.3	22.5	17.4	14.6	12.8	10.1
1	CA	59.8	41.9	39.3	27.9	25.9	22.4	18.6	15.8	13.9	10.6
1	CA	61.1	43.9	41.0	28.5	26.7	22.9	19.0	16.4	14.6	9.8
4	CA+BC	62.4	51.8	49.1	33.0	30.8	26.7	21.7	18.5	15.8	11.4
4	CA+BC	56.1	47.1	45.8	32.7	30.4	26.3	22.2	19.2	16.9	12.3
4	CA+BC	60.3	46.3	43.8	31.6	29.2	24.8	19.6	17.0	15.2	12.2
5	Conv.	58.8	41.9	40.2	28.5	26.8	23.1	19.1	16.5	14.6	11.5
5	Conv.	54.0	41.5	39.4	27.5	25.1	20.3	15.9	13.6	11.9	12.9
5	Conv.	57.8	44.0	42.2	30.3	28.3	23.4	18.5	15.7	13.8	12.6
7	Conv.	56.6	41.5	38.4	28.4	27.0	23.4	20.7	18.0	16.2	11.8
7	Conv.	56.0	40.9	39.0	30.5	28.8	25.3	21.0	18.1	16.1	12.9
7	Conv.	55.8	39.3	37.1	28.6	27.3	24.6	21.0	18.2	16.3	12.3
9	CA+BC	62.8	45.9	42.1	29.3	27.4	24.1	20.2	17.6	15.3	11.9
9	CA+BC	60.8	47.8	45.4	34.0	31.9	27.3	21.9	18.8	16.0	12.2
9	CA+BC	62.2	50.3	47.2	31.0	28.7	24.7	20.5	17.7	15.4	12.3
10	CA	64.0	51.0	48.7	32.7	30.2	25.9	21.2	17.8	15.7	12.7
10	CA	63.1	47.1	44.5	31.0	28.6	24.7	20.3	17.2	15.1	12.3
10	CA	61.1	50.6	49.0	34.5	31.6	26.6	21.1	17.9	15.6	12.8
14	Conv.	60.1	38.4	36.1	28.1	26.8	24.7	21.3	18.7	16.8	12.0
14	Conv.	57.9	37.4	35.2	27.2	26.0	24.2	20.8	18.5	16.8	12.6
14	Conv.	53.6	38.0	35.4	27.2	26.3	24.7	22.3	19.9	18.1	13.7
15	CA	57.9	47.9	45.0	31.2	29.0	24.7	19.8	17.0	15.2	11.7
15	CA	62.5	44.5	39.9	27.4	25.7	22.4	18.9	16.6	14.9	10.5
15	CA	61.7	42.3	37.6	25.9	24.3	21.7	18.5	16.0	14.4	10.6
18	CA+BC	60.1	45.7	41.7	28.2	26.2	22.6	18.3	15.6	14.1	9.9
18	CA+BC	57.3	42.3	40.1	27.3	25.4	22.2	18.1	15.7	14.3	10.4
18	CA+BC	60.9	43.8	39.6	26.4	24.4	21.0	17.3	14.6	13.3	9.6
20	CA+BC	62.0	44.6	41.6	30.5	28.7	25.2	21.0	17.8	16.2	12.0
20	CA+BC	63.2	48.0	44.2	29.3	27.3	24.2	20.5	17.7	16.1	10.5
20	CA+BC	61.2	47.7	43.6	28.4	26.4	23.1	19.5	17.0	15.7	9.9
23	Conv.	53.1	38.8	36.4	27.3	25.5	22.2	18.0	15.0	13.8	12.2
23	Conv.	57.9	41.3	38.6	28.5	26.7	23.3	19.0	16.2	15.0	11.2
23	Conv.	58.7	43.5	40.5	28.6	26.7	24.0	19.3	16.4	15.1	11.0
24	CA	60.3	45.5	44.3	34.3	30.4	25.7	18.3	14.3	13.0	9.6
24	CA	56.6	46.5	44.6	31.8	29.2	24.0	18.2	15.0	13.8	9.7
24	CA	58.2	47.9	45.0	31.4	28.9	24.1	19.2	15.7	14.3	10.1



Appendix 4: *Water retention curves fitted to van Genuchten equation in RETC and applied to an excel line graph where the x-axis shows vol % water content and y-axis displays matric potential on a logarithmic scale. Boxes with black dotted lines show mean drainable water content (water content between saturation and field capacity -100 hPa). a) conservation agriculture (CA)(n=12); b) conservation agriculture + addition of biochar (CA+BC) (n=12); c) conventional practice (Conv.) (n=12); d) Mean values of CA, CA+BC and Conv.*

Appendix 5: *Results from BC pF. Volumetric water content of each sample*

Material	BC dosage	Saturation	Sandbox				Pressure chamber				
			-10 hPa	-20 hPa	-50 hPa	-100 hPa	-100 hPa	-330 hPa	-1000 hPa	-3000 hPa	-15000 hPa
Sand	0 %	43.3	41.1	40.8	12.3	6.2	4.0	2.4	1.6	1.4	1.0
Sand	0 %	45.1	42.4	41.8	10.2	5.5	3.8	2.4	1.6	1.4	1.1
Sand	100 %	43.1	41.7	41.3	10.4	5.8	4.0	2.3	1.6	1.4	1.0
PPBC	2 %	46.5	42.8	42.0	10.9	6.4	4.6	3.3	2.2	7.0	1.2
PPBC	2 %	44.2	42.0	40.1	10.8	6.1	4.4	2.7	1.9	1.7	0.7
PPBC	2 %	46.9	42.6	41.3	10.6	6.3	4.6	3.5	2.2	1.8	0.9
PPBC	5 %	43.5	41.7	40.5	12.0	7.5	5.6	4.1	2.8	2.2	0.9
PPBC	5 %	46.8	42.8	41.1	11.4	7.5	5.6	3.9	2.8	2.1	1.1
PPBC	5 %	45.3	42.5	42.4	12.2	8.0	6.0	3.8	2.7	2.2	1.1
PPBC	10 %	48.8	42.7	40.4	14.6	10.2	8.3	4.9	3.9	3.2	1.7
PPBC	10 %	47.5	43.1	41.3	14.9	10.5	8.5	5.9	4.6	3.5	1.7
PPBC	10 %	48.1	44.5	42.0	14.4	10.3	8.3	6.3	5.4	4.0	1.8
PPBC	50 %	58.1	54.8	51.0	35.8	30.2	27.5	21.2	16.8	14.9	4.1
PPBC	50 %	59.3	55.4	51.8	35.8	30.4	27.7	22.5	21.0	17.7	4.3
PPBC	50 %	57.9	54.8	51.3	36.9	31.1	28.4	21.4	17.9	15.9	4.1
PPBC	100 %	82.0	76.4	70.0	59.2	54.5	51.7	39.7	38.7	31.1	4.4
PPBC	100 %	83.1	77.2	70.4	59.5	54.8	52.1	40.4	39.2	31.1	4.8
PPBC	100 %	84.0	78.3	72.0	61.2	56.5	54.2	48.3	48.5	47.7	4.1
MCBC	2 %	46.6	42.8	41.1	10.7	6.3	4.6	3.2	2.4	2.1	1.8
MCBC	2 %	45.7	42.7	41.3	10.4	6.1	4.2	2.7	2.1	1.8	1.9
MCBC	2 %	48.2	43.7	41.7	9.9	5.8	4.2	2.8	2.2	1.9	1.9
MCBC	5 %	44.7	41.5	41.1	10.7	7.0	5.3	3.6	3.0	2.6	3.4
MCBC	5 %	46.7	43.1	41.5	10.4	6.9	5.4	3.8	3.2	2.7	3.1
MCBC	5 %	46.0	42.5	41.4	10.6	7.0	5.4	3.8	3.0	2.6	3.7
MCBC	10 %	49.2	43.6	41.3	13.1	9.2	7.5	5.5	4.7	4.1	5.2
MCBC	10 %	46.0	42.6	41.2	12.3	8.9	7.3	5.7	4.8	4.3	4.5
MCBC	10 %	46.6	43.9	41.2	12.1	8.8	7.2	5.5	4.5	4.1	4.2
MCBC	50 %	53.6	48.4	42.3	24.7	21.6	19.7	18.6	16.9	15.8	26.8
MCBC	50 %	55.7	50.3	44.7	27.2	24.5	22.0	21.9	20.8	19.6	25.3
MCBC	50 %	53.5	48.5	42.9	26.9	23.8	21.3	20.1	18.5	18.3	22.1
MCBC	100 %	71.0	60.0	45.6	41.2	39.8	37.8	34.2	35.6	32.4	19.4
MCBC	100 %	78.4	64.8	47.3	42.4	41.1	38.9	37.4	33.6	32.4	30.0
MCBC	100 %	75.5	58.5	43.8	39.7	38.5	36.7	34.7	31.2	30.1	20.0
PPBCP	2 %	42.1	38.5	37.8	14.0	8.4	5.3	4.1	2.4	1.9	0.7
PPBCP	2 %	41.4	38.8	37.6	14.1	8.3	5.2	4.1	2.4	1.8	0.6
PPBCP	2 %	41.7	39.3	38.9	13.7	8.3	5.3	4.3	2.5	1.9	0.6
PPBCP	50 %	50.7	42.9	41.0	39.4	30.4	26.7	22.4	22.1	18.8	2.6
PPBCP	50 %	56.7	43.1	40.6	40.2	31.3	26.9	22.4	18.5	17.5	2.3
PPBCP	50 %	50.1	41.5	39.3	38.6	29.4	25.6	23.0	19.6	18.4	2.2
MCBCP	2 %	42.7	39.1	37.9	14.3	7.5	4.1	3.1	1.8	1.4	0.8
MCBCP	2 %	44.7	39.3	38.8	14.4	7.5	4.2	2.9	2.1	1.5	1.0
MCBCP	2 %	46.7	43.4	42.2	18.5	11.5	8.1	7.5	6.2	2.0	0.6
MCBCP	50 %	48.2	44.1	42.4	42.9	36.3	31.1	26.0	24.3	17.9	2.7
MCBCP	50 %	49.2	43.7	42.7	43.1	36.4	32.3	28.7	25.1	19.6	3.1
MCBCP	50 %	47.7	43.5	41.8	42.2	35.7	31.9	28.1	26.1	21.2	3.3

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway