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The Impact of Planting Basins Under Conservation Farming with and Without Biochar on Aggregate Stability, Soil Organic Carbon, and pH in Zambian Acrisols

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Preface and Acknowledgements:

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Ås, 15 May 2018.

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Abstract

Conservation Farming (CF) in Sub-Saharan Africa (SSA), including reduced tillage, return of crop residue, and crop rotation, has been found to increase maize yields in rain-fed agriculture. In combination with the application of biochar (BC), crop productivity may be further enhanced. Although increased yields have been attributed to improved soil physical and chemical properties, the number of studies supporting this claim are few, especially in Africa where adoption is relatively recent, and where mechanistic understanding of the underlying process and the long-term effects are limited. This study addresses the impact of CF with and without BC on soil properties such as soil organic carbon (SOC), pH, and aggregate stability. This is done by using two separate research fields in Mkushi, Zambia on Acrisols. One focuses on three years of different CF techniques, where CF, CF with and without residue retention, and CF with BC are compared to conventional practises (farm trials). A second site focuses on BC dosage and size of BC particles (BC trials).

In both trials, soil properties including the aggregate stability, pH, soil organic carbon (SOC), total nitrogen (N), and hot water extractable carbon (HWEC) a proxy for labile carbon, were used to interpret soil quality differences between treatments, and their changes over time. Results showed significant improvement of aggregate stability in CF planting basins relative to outside of basins. The positive effect of CF basins was also found for SOC, total N, and HWEC, but not for pH, highlighting the importance of planting basins as an aspect of CF. The labile fraction increased significantly in CF plots compared to conventional, but the SOC content did not. Comparing these finding from early 2018 to those from the start of the experiment in late 2015 highlight minimal changes in total carbon (C), organic C, and total N. However, a distinct decrease in pH was found, probably in response the gradual loss of lime after its application in 2014.

Conservation farming in combination with BC did not improve aggregation, but did significantly increase SOC. However, HWEC did not increase with BC but rather decreased. indicating BC amendment does not increase the labile carbon fraction, and might actually suppress it, which can negatively impact soil properties such as nutrient cycling.

A study by Obia et al. (2016) found significant results linking increased BC with improved aggregate stability one and two years after BC application in Mkushi. Their conclusion was not confirmed by this study which found no correlation of increased BC dose or size with aggregate stability. However, HWEC correlated significantly to aggregate stability. Indicating HWEC is a major driver of aggregation, whilst BC is not. Thus, the labile C associated with fresh BC should be further researched to determine if the increase in aggregate stability due to BC is actually caused by HWEC, which is high in fresh BC and reduces over time.

Table of Contents

Preface and Acknowledgements:	ii
Abstract	iv
Table of Contents	v
Introduction	1
Conservation Farming:	1
Biochar:	6
Aggregate Stability:	7
Soil Organic Carbon and Chemical Properties:	8
Objectives:	10
Hypotheses:	11
Experimental Site	11
Farming practices long term experiment (Farm Trials):	13
Biochar Size and Dosage experiment (BC Trial):	14
Sampling	16
Methods	16
Pre-Treatment:	16
pH:	16
TOC and Total N:	17
Aggregate Stability:	17
Hot Water Extractable Carbon (HWEC):	18
Statistical Analysis:	18
Results	19
Aggregate Stability:	19
Farm Trials:	19
Biochar Trial:	19
pH and Total Organic Carbon :	20
Farm Trials:	20
Biochar Trial:	21
HWEC:	22
Farm Trials:	22
Biochar Trial:	23
HWEC and SOC:	24
Farm Trials:	24
Biochar Trial:	24
Discussion	26
SOC, Total N, and pH:	26
HWEC and SOC:	27
Soil C/N Ratio:	28
Aggregate Stability:	29
Aggregate Stability and HWEC:	30
Long-Term Effects of Biochar on Aggregate Stability:	31
Farm Trial vs BC Trial:	33
Comparisons to Other Studies – Farm Trials:	34
pH:	35
Total Carbon:	35

Organic Carbon:	36
Total Nitrogen:	36
Seasonality of HWEC:	37
Possible Improvements to Study	38
Conclusion	38
Supporting & Disproving the Hypotheses:	38
References	41
Appendix	47
Appendix 1: Statistical Analysis	47
Farm Trials:	47
Biochar Trial:	48
Appendix 2: Additional Data: Total Nitrogen.	49

List of Figures:

- Figure 1: Conventional vs CF soil preparation.
- Figure 2: Farm trials in September 2017 (hot dry season). Normal CF plot with visible residues.
- Figure 3: Farm Trials in February 2018 (warm wet season) under maize production
- Figure 4: Biochar production using the "Kon Tiki" fire curtain method in a conical hole at the experimental site in Mkushi.
- Figure 5: Agro-ecological zones of Zambia, and location of Mkushi.
- Figure 6: Experimental Setup of farm trials in Mkushi.
- Figure 7: Example of planting basins.
- Figure 8: A field of planting basins with applied lime
- Figure 9: Biochar Trial setup.
- Figure 10: Aggregate stability (%) of farming trials
- Figure 11: Aggregate stability (%) of Biochar trials
- Figure 12: Total Carbon (%) and pH for farm trials.
- Figure 13: Total C (%) and pH of biochar trials.
- Figure 14: Correlation of Total C (%) and pH in the BC Trial
- Figure 15: HWEC (mg/kg) of farm trials
- Figure 16: HWEC (mg/kg) for BC trials
- Figure 17: Correlation of Total carbon (%) and HWEC on farm trial plots
- Figure 18: Total carbon (%) is graphed against HWEC (mg/kg) for BC trial values
- Figure 19: HWEC is presented as a percentage of total carbon. For farm trials
- Figure 20: HWEC as a percentage of total carbon for BC trial
- Figure 21: Correlation of aggregate stability (%) and HWEC (mg/kg) for farm trial
- Figure 22: Aggregate stability (%) correlated to HWEC (mg/kg) and TOC (tot C%).
- Figure 23: Dosage of BC (w/w%) graphed against aggregate stability (%) for BC trials. Includes results from Obia et al. (2016)
- Figure 24: box plot of pH inside and outside basins for 2015
- Figure 25: box plot of pH inside vs outside basins for 2017
- Figure 26: HWEC (mg/kg) in September 2017 (pre-growing season - dry season) and HWEC from February 2018 (mid growing season - wet season)

List of Tables:

- Table 1: Farm Trial Soil C/N Ratio
- Table 2: BC Trial soil C/N Ratio
- Table 3: Comparing data of farm trials to background data, past studies, and unpublished data from 2018.
- Table 4: Summary of statistical analysis done, and critical values of farm trial data (appendix 1)
- Table 5: Summary of statistical analysis done, and critical values of BC trial data (appendix 1)
- Table 6: Total nitrogen (%) of farm trials (appendix 2)
- Table 7: Total nitrogen (%) of BC trial (appendix 2)

List of Abbreviations:

- CF: Conservation farming
- CA: Conservation agriculture
- BC: Biochar
- SSA: Sub-Saharan Africa
- GHG: greenhouse gas
- C: Carbon
- N: Nitrogen
- Tot C: Total carbon
- Tot N: Total nitrogen
- Org C: Organic carbon
- SOM: Soil organic matter
- SOC: Soil organic carbon
- HWEC: Hot water extractable carbon

Introduction

New farming practises are under continuous development to keep up with a growing global population and the increasing need of improved global food production. Under a changing climate and prominent soil degradation the need for sustainable, efficient, and climate smart agriculture is of all the more importance, especially for small-scale rainfed agriculture. One such practice is Conservation Farming (CF), a technique created to improve soil quality whilst increasing yields (Aagaard 2012). CF is increasing in adoption of use and in research, as it has proved efficient in improving soil properties and food production in several locations, including Zambia. Biochar (BC) has also been used in the quest to improve agricultural soils and production, but also to store carbon (NGI 2018).

Conservation Farming:

Conventional farming traditionally includes ploughing, intensive monocropping and burning of residues, something which over time has degraded the soil. The major issues surround the soil structure, causing significant erosion and low water holding capacity, as well as low soil fertility, where nutrients and soil organic matter (SOM) are lacking. Degraded soil directly impacts food production and yields, causing major issues for food security, and the livelihoods of small scale farmers. To combat soil degradation methods of CF have been implemented all over the world.

Conservation farming originates from techniques implemented following the US Dust bowl during the droughts of the 1930s (CFU 2018), where the main goal was to reduce soil degradation and erosion. From there it has expanded to accommodate a variety of locations and issues. In Africa the main needs of farmers are to lower costs and increase yields, whilst accommodating for climatic changes and increased food demand (CFU 2018). The IPCC predicts increased uncertainty in precipitation and lowered soil moisture with climate change, and as a continent with already high food insecurity, climate smart agriculture is of grave importance. Climate smart agriculture highlights the need of agricultural systems to increase yields and incomes sustainably, adapt to climate change, and to reduce greenhouse gas (GHG) emissions (FAO 2018). Thus, adapting, and mitigating climate change through better practises and technologies along with improving policies to accompany these needs. Notably climate smart agriculture has been associated with increasing carbon sequestration of soils. Africa is

also the continent with the lowest rates of adoption (Farooq and Siddique 2015), so research into CF in new environments is important for future use and understanding.

Conservation farming is based on three main aspects: zero-tillage /minimum tillage, residue retention and soil cover, as well as crop rotation, (Cornelissen et al. 2013, Martinsen et al. 2014). Occasionally weed control (Farooq and Siddique 2015) and nutrient management (Dordas 2015) are included as a fourth aspect. These three changes to farming practises have been found to improve soil properties and farm yields. Conservation Agriculture (CA) is used to describe CF used in addition to *Faidherbia albida* trees, a nitrogen fixer, which have been found to increase fertility and yields of several crops, in particular maize (Shitumbanuma 2012).

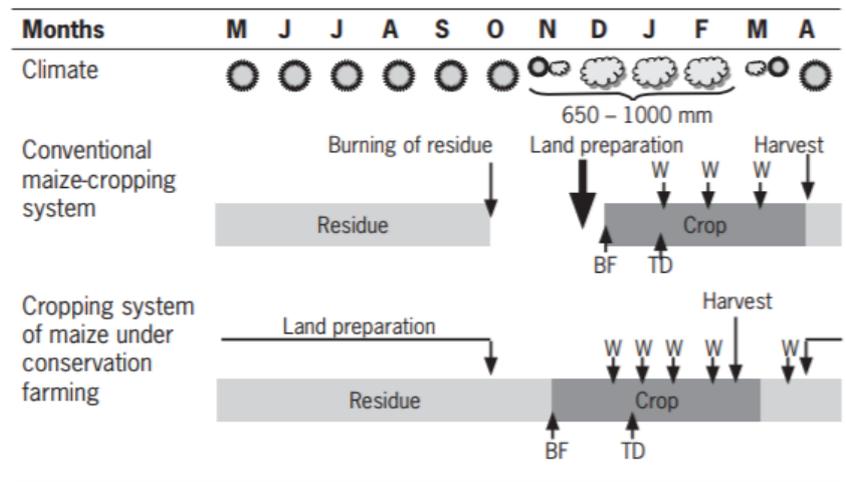
Minimum tillage and zero tillage advocates the use of either rip lines or planting basins. Rip lines use either mechanical or animal draft power to create groves over the field which are opened each season. These lines are placed across from the slope to reduce runoff and erosion when it rains. Rip lines reduce the amount of soil disturbed, but also reduce labour and time as well as fuel use (if mechanised) (CFU 2012). Alternately, if animals or equipment are not available, planting basins are used. Precise basins are dug manually using a hoe where the size of basins and distance between them are measured to set values (13x15x20cm). Basins are also permanent in the field and are opened each season. Both these techniques reduce soil disturbance to 10% of total land, compared to conventional ploughing which overturns entire fields (Goeb 2013).

By minimizing soil disturbance physical soil degradation can be reduced; including erosion and water runoff (Putte et al 2010, Serraj and Siddique 2012). The reduction in tillage is not only important for soil properties but is important for resource management. The specific localisation and quantification of external inputs helps reduce cost and necessary amounts of fertiliser and BC. This is done by using measured amounts of inputs within the basins, such that the inputs are located where it can be of use to the plants, this also improves the nutrient use efficiency (Raun and Johnson 1999).

Residue retention: allowing residues to remain on top of the soil, or mixed within the top soil, helps increase SOM, and protects the topsoil from eroding (Thierfelder and Wall 2009). Crop rotation with legumes can improve the nutrient balance due to nitrogen fixation, increasing the nitrogen availability within the soil (Farooq and Nawaz 2014), and reducing the risk of plant disease (Tarkalson et al 2006). Minimum tillage, residue retention and crop rotation make up CF, but there are still variations within this description. This includes the type and accuracy of

minimum tillage, which plants are used in rotation, and what residues are used, and whether they are only added to the surface or mixed within the soil.

Weeds are of an increased concern in CF systems, such that herbicides are becoming a necessity (Singh et al. 2015). The timing and precision of management is also of increased importance under CF. Where preparations are ideally done earlier than conventional, and planting is started at the onset of the rains (Baudron et al 2007), the difference in timing can be seen in figure 1.



W: weeding – weeding; BF – basal fertilization; TD – ammonium nitrate topdressing

Figure 1: Conventional vs CF soil preparation. Source: Baudron et al. (2007).

In addition to improving soil properties, increasing yields and, being climate smart, CF is also of economic and social benefit, as CF has been found to reduce costs, labour, and overall improve the efficiency of small scale farming (FAO 2015a).

The implementation of the three main elements of CF have many benefits associated with it, but there is still a lack of knowledge of the process and effects on soil and yields, and large disparities in the effects of CF. A recent study in Zambia found no differences between conventional and CF on soil properties (total carbon and SOC), and no improvement due to basins (Martinsen et al. 2017). Whilst Thierfelder and Wall (2009) and Thierfelder et al. (2013) found improvements in yield, carbon, aggregate stability, and water infiltration in CF compared to conventional on multiple sites in Zambia over several seasons. The impact of CF in SSA seems to be highly reliant on the initial soil properties, soil type and climate, especially to the soil moisture and water holding capacity (Giller et al. 2009). Similarly, to CF, the effect of BC in agricultural systems have produced inconsistent results, often showing dependency on site and soil type (Cornelissen et al. 2013).

Studies often focus on different sites and/or treatments, whilst studies focusing on the same sites over time are less common. This study investigates both, as five CF treatments are researched at a site in Mkushi Zambia which has been sampled continuously since 2015. In addition, another study with focus on BC, established in 2012 is researched, this study will focus on soil properties often related to soil quality; this includes SOC, labile carbon (HWEC), pH and aggregate stability.

Figure 2 and 3 visualise a farm using CF practises. Figure 2 of the non-growing season shows residue retention on the surface, whilst figure 3 in the midst of the growing season depicts grown maize in precise rows.



Figure 2: Farm trials in September 2017 (hot dry season). Normal CF plot with visible residues. Photo: NGI, 2017



Figure 3: Farm Trials in February 2018 (warm wet season) under maize production. Photo: Ellingsen, 2018



Figure 2: Biochar production using the "Kon Tiki" fire curtain method in a conical hole at the experimental site in Mkushi. Photos by Talmo 2018.

Biochar:

Biochar is the charcoal output when biological material is combusted under the absence of oxygen, known as pyrolysis (Pandit et al. 2017). This process results in a BC with a high carbon content, and low ash content that is stable in soils. BC is used to improve soil quality, sequester carbon, and additionally, in amending contaminated soils by its high adsorption ability (NGI 2018).

Biochar production can be done by a variety of methods including traditional kilns made of bricks, or of earth mounds. More recently a flame curtain kiln was developed. Organic waste from numerous feedstock, such as maize cobs, rice husk and pigeon pea can be used, depending on what is available at the given location. Flame-curtain methods; “Kon Tiki” kilns, can be operated in a simple conical hole in the ground (Figure 4) and have reduced emissions of toxic greenhouse gases such as methane and nitrous gases, without reducing the BC quality (Pandit et al. 2017, Cornelissen et al. 2016). This method is also cheap and simple and can be used at most locations. Therefore, it has been used in Mkushi at the site of the CF experiment.

Biochar input to agricultural systems has been found to increase SOC levels, soil pH, cation exchange capacity (CEC), and base saturation (Martinsen et al. 2015). In addition, increases were found in root biomass (Albiven et al. 2015), and nutrient availability (Alling et al. 2014), as well as reduced compaction, improved water retention, and aggregate stability (Obia et al. 2016). Biochar amendment has improved yields in several locations including maize yields in Zambia, some locations present greater effects than others specifically those with sandy soils and a low pH. Significant effects on yields were not found in more loamy soils, as for example those in Mkushi (Cornelissen et al. 2013). Previous research in Zambia indicates that one of the main limiting factors in yield and overall plant growth is water availability, such that the improved water retention associated with BC amendment is of increased importance (Cornelissen et al. 2013).

There is limited information of the impact of BC in combination with CF, but some do indicate enhancements to soil, however the focus is mostly on pH (and CEC), water retention, and crop yield (Martinsen et al. 2014). Other studies, such as Obia et al. (2016) have investigated the short-term effects of BC size and dosages on aggregate stability, bulk density, porosity, and water retention of conventional plots and found positive effects. This study also investigates aggregate stability at this site to see if the results are replicable and to determine the impact over time. Additionally, pH is measured to determine whether the pH increasing effect of BC

lasts long-term. SOC and labile carbon is also included to investigate the relationship between aggregation and soil carbon. This was done on the same sites as Obia et al (2016) with a trial of BC in combination with CF on a farm trial, and on BC size and BC dosage.

Aggregate Stability:

Conservation farming with and without BC have been found to affect physical soil properties such as soil structure and aggregate stability. One of the major driving forces in the development of CF was reducing erosion, which is one of the most researched and consistent improvements associated with CF (Giller et al. 2009, Lal 1998). As well as reducing erosion CF is also found to improve soil structure by reducing compaction (reducing bulk density), improving water infiltration and retention, and increasing aggregate stability (Farooq and Siddique 2015, Lal et al. 2004).

Aggregates are soil particles that cohere together, more so than to neighbouring soil particles, and aggregate stability is a measure of how strong these bindings are; how much external stress (water and wind) they can withstand (Kemper and Rosenau 1986). Aggregation is dependent on clay binding and biological processes (Brady and Weil 2009). Biological processes are influenced by SOM, which increases microbial decomposition, and the products of which can bind compounds. Increased SOM also improves the stability of soils and improves soil structure particularly in sandy soils (Blume et al. 2016, FAO 2015a).

Tillage (ploughing) can both improve and harm aggregation (Pagliai et al. 2004, Hamza and Anderson 2005) this is dependent on the soil itself, but generally aggregation is reduced over time. The latter may be due to a reduction of SOM, due to oxidation of the soil as it is continuously moved. Infiltration and porosity have also been found to reduce under long-term tillage, whilst bulk density and surface crust formation increases (Pagliai et al. 2004). Well-aggregated soils have pores within and around aggregates, improving the porosity. This reduces the bulk density (compaction) and improves water infiltration. Less aggregation and higher compaction results in water runoff and higher erosion and can constrain root growth (Speratti et al. 2015).

Minimum tillage is linked to improved aggregation and increased SOC, where both can be used as indicators of soil quality. Therefore, both SOC and aggregate stability, and the relationship between these, are of interest in determining the impact of CF and BC on soil quality. Two aspects of CF are the minimising of tillage and the increase in SOC from plant cover, which

have both been found to improve aggregation, so this study will investigate the impact of CF, and CF with mixed residue and without residue retention on aggregate stability. Also, the impact of BC will be investigated both in combination with CF and in a separate study with focus on BC size and dosage. A recent study by Obia et al. (2016) found significant positive short-term impacts of BC on aggregation, where increasing BC dosage resulted in a higher percentage of stable aggregates if this relationship is still found is of interest in this study.

Soil Organic Carbon and Chemical Properties:

Soil represents a major global carbon stock, which is comprised of soil organic carbon (SOC) from photosynthesis and decomposition and soil inorganic carbon (SIC) as carbonate minerals (Wang et al. 2012). Soil carbon (C) loss is one of the main factors of soil degradation alongside erosion and nutrient loss (Srinivasarao et al. 2015). Conservation farming can theoretically restore carbon sequestration in poor soils over a period of five to ten years (Lal 1997) however, more recent studies show that realistically this is not the case (Cornelisen et al. 2018).

All organic substances are comprised of C, such that SOM is made of approximately 50% C (Lal 2004). The primary source of SOC is plant residues whilst microbial respiration is the main pathway of carbon loss (as CO₂). The decomposition of SOC is also a source of nitrogen and other nutrients and is important for plant uptake (FAO 2015b). Residue incorporated into the soil is more readily available to soil organisms than on the surface (Brady and Weil 2009), which can be important when analysing the residue retention associated with CF. Soil organic carbon is also linked to improved aggregation and soil structure, which in turn improves water holding capacity and infiltration. Residue retention can increase SOC and will also help maintain a cooler and wetter topsoil, which improves conditions for microbial decomposition of SOC (Follett 1993).

The labile pool of SOC is the most readily available fraction for microorganisms and is responsible for improved nutrient availability due to its easy decomposition. The passive SOC pool, which is complex and stable, is important for C sequestration and the water holding capacity of the soil. Thus, the labile part of SOC is easily lost and easily gained, whilst the passive part is stable and changes very slowly over time. Therefore, in response to management and tillage, changes in SOC are largest for the labile fraction, whereas changes to the passive fraction are far more limited (Weigel et al. 2011). This quick response in labile SOC results in noticeable changes to soil characteristics such as nitrogen mineralisation and aggregate stability

over short time frames. Both stable and labile SOC is important for soil quality and plant growth, such that both decomposition and accumulation are important processes. Natural vegetation has higher SOM than agricultural lands, due to little return of SOM to the soil (Martinsen et al. 2017). Therefore, agricultural systems need to incorporate minimal tillage and preferably use residues such as litter and roots, manure, and compost to maintain high SOC levels (Brady and Weil 2009). Long term studies have found increases in SOC under CF and a decrease under conventional practises, effective in most soil types and systems (Thierfelder et al. 2013, Conant et al. 2013, Basso et al. 2015, Conant et al 2007, Basso et al. 2015). Contradictory, Giller et al. (2009) concluded that SOC did not increase due to minimum tillage practises, but by the increased input of biological matter by maintaining soil cover. It is uncertain which aspects of CF influence which properties. More research is needed, which is why this study investigates CF with and without residue retention, as well as normal CF and conventional (no tillage) to see if SOC varies more due to residue or tillage.

Both CF and BC are connected to the increase in SOC and total C, but there is limited information on the impact of the combination of CF and BC on SOC. This study will further investigate the impact of CF and residue retention, as well as BC on SOC and the labile carbon fraction, using hot water extractable carbon (HWEC) as a proxy. HWEC represents the fraction of carbon extractable in hot water; this includes the microbial biomass, simple organic compounds, and hydrolysable compounds. HWEC closely relates to microbial biomass, nitrogen (N) availability, and the easily available labile SOC pool (Ghani et al. 2003). Due to its relationship with labile SOC, HWEC acts as a sensitive measure to environmental short-term change, such as soil temperature, soil moisture, and tillage (Weigel et al, 2011, Leinweber et al. 1995). HWEC contributes between 3 and 5 % of total C (Leinweber et al. 1995). HWEC is used to represent the labile carbon pool and is explored further in its importance in CF and BC treatments. Specifically, the relationship between SOC and aggregation, which has previously been positively correlated (Haynes and Francis 1993), as well as seasonality and possible C sequestration. Labile carbon does not contribute to carbon sequestration as it is not in a stable form, such that increased labile C, does not directly increase carbon sequestration. Only a very small fraction of labile C becomes long term-stable carbon which contributes to C sequestration.

pH is the chemical measure of the acidity and alkalinity of soils. Soil pH is a factor in determining the solubility of micronutrients and toxicity of metals (Thomas 1982) and is a standard in soil analysis. African soils are often highly weathered and acidic. BC has been

shown to increase pH (Alling et al. 2014, Martinsen et al. 2014, Obia et al. 2015), the scale of which depends on BC type, quality, and amount as well as the soils initial properties (CEC) (Alling et al 2014., Martinsen et al 2015). Less consistent results have been found for pH and CF, but some studies show significantly increased pH values inside CF basins compared to outside basins and conventional plots (Mazvimavi 2008, Martinsen et al. 2015). The relationship between pH and BC has been found such that BC increases pH significantly after initial amendment, but studies such as Cornelissen et al. (2018) found the effect of BC faded after two to five growing seasons. So, it is of interest to see if BC amendment in both trials in this study have maintained a BC induced pH effect after three to five growing seasons. pH is included as an important measure to compare previous studies, it is also included to study the long-term relationship between BC and pH.

Conservation farming and BC have been suggested to improve several soil properties and be a viable solution to deal with food insecurity, climate change and soil degradation, but such positive effects have not been found everywhere. Conservation farming has been connected to improvements in erosion, nutrient availability, pH, SOC, aggregate stability and increased yields and improved efficiency in labour and fuel use (CFU 2018, Thierfelder et al. 2013, Karlen et al 2013). Whilst BC has been found to improve pH, CEC, compaction, aggregate stability, water infiltration, GHG emission reductions, and carbon sequestration (Martinsen et al. 2014, Obia et al. 2016, Cornelissen et al. 2016). However, there is high variability of results found in past research. Climate and soil type is a main factor impacting the effect CF and BC have on soil properties, and a main reason behind variable results. Many studies aim at long term effects, which few have had the opportunity to research. This study will focus on two separate experimental sites, one with focus on CF, and variations including CF with mixed residue, CF without residue retention, CF in combination with BC, and conventional practises. The second study is based specifically on BC dosage and sizes.

Objectives:

- Assess five different management practises including CF, CF in combination with BC, CF with mixed residues in basins, CF without residue retention and conventional farming practises, inside and outside planting basins. Specifically, their effect on aggregate stability, SOC, labile carbon and pH.

- Evaluate the long-term effects of BC dosage and size on the same soil properties: aggregate stability, SOC, labile carbon and pH.
- Compare analysed data to that of previous seasons and studies to see if impacts are consistent and determine changes over time. This includes changes in aggregate stability with BC amendment, changes in pH and carbon under CF farming trials, and the seasonality of the labile carbon pool.

Hypotheses:

1. CF practices result in improved soil properties: greater aggregate stability, greater SOC content, greater labile carbon, and a higher pH than conventional practices.
2. We expect the use of planting basins to increase SOC and HWEC (larger values inside than outside basins).
3. BC is positively linked to increased aggregate stability, pH, and the carbon content of soil as documented by previous studies (Martinsen et al 2014, Obia et al. 2016).
4. Improvement of soil quality in CF plots, but not in conventional plots since start of the experiment in 2015.

Experimental Site

Located in Mkushi, Central Province in Zambia, two experimental sites are used. One with focus on several CF practises, whilst the other focuses on BC. Mkushi is located in Agroecological region IIa (see figure 5), where unimodal annual rainfall ranges from 750-1000 mm. The climate is subtropical and temperature ranges from 20-33°C (Frenken 2005). Both trials are rainfed farming systems (not irrigated).

Farming practices long term experiment (Farm Trials):

- Location: 13°45'684" S, 29°03'349" E
- Soil type: Sandy Loam Acrisol
(Obia et al. 2016)

The first experimental setup is based on farmer practises and CF. Started in 2015, a conservation farming trial of 11 treatments was set up, with four repetitions randomly spaced within four blocks, with a total of (4 x 11) 44 plots. Within each plot there are 4 rows with 6 basins; 24 basins per plot, and a total of 24 x 44 basins in the entire trial. The treatments are based on maize production (2015 and 2017), with biannual rotation with legumes (soya beans in 2016). Between each block there are borders of non-trialled maize (figure 6). Of the 11 treatments, five will be the focus of this study; conservation farming normal, conservation farming with BC, conservation farming with residue mixed into the basin, conservation farming without residue, and conventional farming. All treatments are further described below.

Conservation Farming Normal (CF): The land preparation is based on minimum disturbance principles, where basins of 15 x 20 x 40cm are prepared each dry season, example of such basins can be seen in figure 7 and 8. Fertiliser (NPK) and top dressing (urea) are added into basins. Fertiliser “Compound D” (N, P₂O₅, K₂O, 10:20:10) was applied at a rate of 200 kg ha⁻¹ yr⁻¹ before planting, and urea (46:0:0) applied at a rate of 100 kg ha⁻¹ yr⁻¹ about 4 to 5 weeks as well as 8 weeks after planting (total of 200 kg ha⁻¹ yr⁻¹). Herbicides are also used. Residues are placed between rows of plants (outside basins) and over plots after harvest. Crops are rotated annually between maize and legumes (Cornelissen et al. 2013).

Conservation Farming + 4t/ha PP (Pigeon pea) Biochar (CF + BC): Following similar land preparation strategies as CF normal, these plots also have residue retention and the same amounts of top dressing and fertiliser, however the basins are not fully opened each year, and shallow preparation methods are used. Where only the top soil is removed before adding fertiliser and seeds. The BC is made from pigeon pea (PP) feedstock using the Kon Tiki flame-curtain method. Where feedstock is added slowly, layer by layer, such that the flames burn escaping syngas, and protect the underlying BC from oxidation. The method is conducted in a conical pit dug into the ground (1.5m deep and 2.5m wide) (figure 4). The peak temperatures during pyrolysis is 575°C (Cornelissen et al. 2016).

Conservation Farming with mixed residue in basins (CF mixed residue): The basins are fully opened each year, when half of the residue (leaves) is mixed with the soil within the basins,

while the other half is left on the surface (the stems and some leaves). The basins are closed after mixing in residues and shallow preparations, like that of BC plots (same amount of fertiliser and top dressing used) are completed.

Conservation Farming with no residue (CF no residue): Similarly, to CF, the basins are fully opened each season and preparation follows regular additions of fertiliser and urea. However, all residues are removed after harvest, removing one aspect of CF which is residue retention.

Conventional Farming (Conv): Regular conventional preparations, where planting basins are not used, such that the location of planting varies annually. Digging starts at the onset of the rains, and all residue is removed. The same amount of urea and fertiliser is used; however, fertiliser is not added at the same time as sowing, but after emergence of the plants.

Biochar Size and Dosage experiment (BC Trial):

- Location: 13°44'839" S, 29° 05'972" E
- Soil type: Loamy Sand Acrisol
(Obia et al., 2016)

The second field experiment with focus on BC size and dosage, was set up in Mkushi in April 2013. Comprising of plots of three BC dosages (0, 2, and 4 w/w%), and three BC sizes (≤ 0.5 mm, 0.5-1mm, and 1-5 mm), and reference plots (0 dosage) were established under conventional farming practises (figure 9). Biochar sizes are described as fine, medium, and coarse, whilst dosage is presented as 0, 2, and 4 w/w%.

Corn cob BC was produced in a brick kiln at temperatures of 350°C over a period of one day. The BC was mixed with the top layer of soil (0-7cm) and the underlying layer was loosened with a hoe, to avoid any hard pans. Fertiliser was added before sowing maize (Obia et al. 2016).



Figure 7: Example of planting basins. Where distance between each basin and each row is measured to create a precise minimum tillage system. Photo: Talmo 2018



Figure 5: A field of planting basins with applied lime. Photo: CFU Zambia <https://conservationagriculture.org/gallery>



Figure 6: Biochar Trial setup. BC dosage and BC size (3x3x3 plots). Photo: Martinsen 2013.

Sampling

Sampling of the Mkushi farming practice experiments was done in September of 2017. Residue was moved before soil was collected from the upper 10 cm. Soil was combined from three locations within treatments in a bulk sample from within planting basins, and a separate sample was combined for the outside of basins. For the conventional plots where basins are not used the samples classed as “outside” were taken outside the planting rows, whilst those classified as “inside” were taken closer to the planting stations. This was done for all five treatments, for all four blocks, totalling 40 samples.

Sampling from the BC experiment was done in October 2017. Where soil samples were taken from the upper 7 cm of soil. This was done for treatments with each BC size and dosage (Fine-2, Fine-4, Medium-2, Medium-4, Coarse-2, and Coarse-4) as well as a reference plot sample (Ref-0), a total of 7 samples.

Methods

Pre-Treatment:

All soil samples were air dried for at least 48 hours and sieved through a 2 mm sieve. Samples from the BC trials were forced through the sieve, whilst that from the farming trials were not. Further sieving was done for aggregate analysis, into aggregate fractions 1mm to 2mm, and 0.25mm to 1mm. A subsample of all soil samples was milled for 3 minutes using a mechanical mortar, for carbon and nitrogen analysis.

pH:

The pH of the soil was measured by combining 10ml of homogenous sieved soil (2mm), and 25 ml deionized water, and shaking well. The mixture was left over night before being shaken again 30 min before measuring the pH electrochemically using an Orion pH meter. The pH meter was calibrated using solutions of pH 4 and pH 7, and the pH probe was rinsed between each sample.

TOC and Total N:

Total carbon and nitrogen is analysed using the Leco TruSpec CHN instrument. Total carbon is analysed using dry combustion methods described in (Nelson and Sommers 1982). And total nitrogen is derived using Dumas methods described in (Bremner and Mulvaney 1982). As an independent analysis of organic C was not included in this study total C will be discussed as TOC. Results of Tot C are almost equal to Org C, due to the low pH of the soil (Martinsen et al. 2017).

Aggregate Stability:

Aggregate stability was determined using the wet sieving method, based on methodology described in the user manual for the Eijkelkamp apparatus (Eijkelkamp 2008).

Aluminium tins were used for the distilled water (H₂O), and plastic cups were used for the sodium hydroxide (NaOH) solution to avoid any reaction. 2g/l NaOH is used for this soil as the pH was under 7, in following with the apparatus manual (Eijkelkamp 2008). Before each round the tins and cups to be used were labelled and weighed to give the empty weight.

First eight labelled aluminium tins were filled with water and placed in the apparatus under the sieves. Then 4g of soil was weighed and placed on pre-moistened sieves in the apparatus. The fractions of soil were matched to those of the sieves (0.25-1mm and 1-2mm). The sieves are then lowered into the water and set to run for 10 minutes. After which the sieves are raised and allowed to drain until water is no longer dripping from the sieves. The soil dispersed in the water represents the unstable aggregates. Then the tins of water are replaced with plastic cups filled with 60ml of 2g/l NaOH solution. The sieves are then lowered in the solution and allowed to run for 10 minutes. A spoon was used to help break the aggregates into solution, before running for a few minutes more and being allowed to drain. The stable aggregates should now be in the NaOH solution, and these cups are placed alongside the tins of water in an oven at 40°C until all liquid has evaporated. This takes between 24 and 48 hours. The material remaining on the sieves is sand, BC, or plant residues and as this does not contribute to either stable or unstable aggregates, is not included in the equation. When both unstable aggregates in the tins and stable aggregates in the cups are dried, they are weighted.

The mass of the NaOH in the dried stable aggregates is accounted for by determining the weight of 2g/l in 60ml of solution, which is 0.12g. This value is subtracted from that of the stable aggregates.

Aggregate Stability =

$$\frac{(\text{Stable aggregates} - \text{cup mass} - \text{mass of NaOH})}{((\text{Stable aggregates} - \text{cup mass} - \text{mass of NaOH}) + (\text{Unstable aggregates} - \text{tin mass}))} * 100\% \quad 1$$

Equation 1 is used, where the stable aggregates are found by subtracting the mass of the cup and dried NaOH from the total weight of the second tin. Whilst unstable aggregates are found from the total weight of the first tin subtracting the weight of the tin itself. The aggregate stability fraction is derived by dividing the stable aggregates by the sum of stable and unstable aggregates. After multiplying by 100%, aggregate stability is presented in percentages.

Hot Water Extractable Carbon (HWEC):

HWEC methodology was based on (Ghani et al. 2003) with some adjustments.

Soil samples sieved at 2mm were used for this analysis. First 5g soil was weighed into 50ml plastic tubes. 30ml distilled water was added, and then shaken in a mechanical shaker for 2 minutes. All samples were then added to a water bath set at 80°C, and left overnight for 16 hours, this should extract labile soil carbon. The samples were then centrifuged at 2500rpm for 10 minutes before filtration. Filtering at least 10ml of the solution through 0.45 µm filters and into smaller 15ml plastic tubes. Samples were then sent for DOC analysis by combustion catalytic oxidation methods using the Total Organic Carbon Analyzer TOC-V CPN by Shimadzu (Shimadzu 2017). Results of HWEC are presented as mg/kg.

Statistical Analysis:

Completed in Microsoft Excel version 1803 statistical analysis for variance was done by one-way ANOVA at 95% accuracy. If variance yielded significant further significance was found using the Tukey Test HSD for each treatment inside and outside basins (total of 5x2 groups) where critical values for significance are from Harter (1960) table at 90% accuracy. Significance between two variables was found using two-tailed T-tests at 95% accuracy. And correlation was analysed using correlation analysis (R^2) at 95% accuracy, further specifics can be found in Appendix 1.

Results

Aggregate Stability:

Farm Trials:

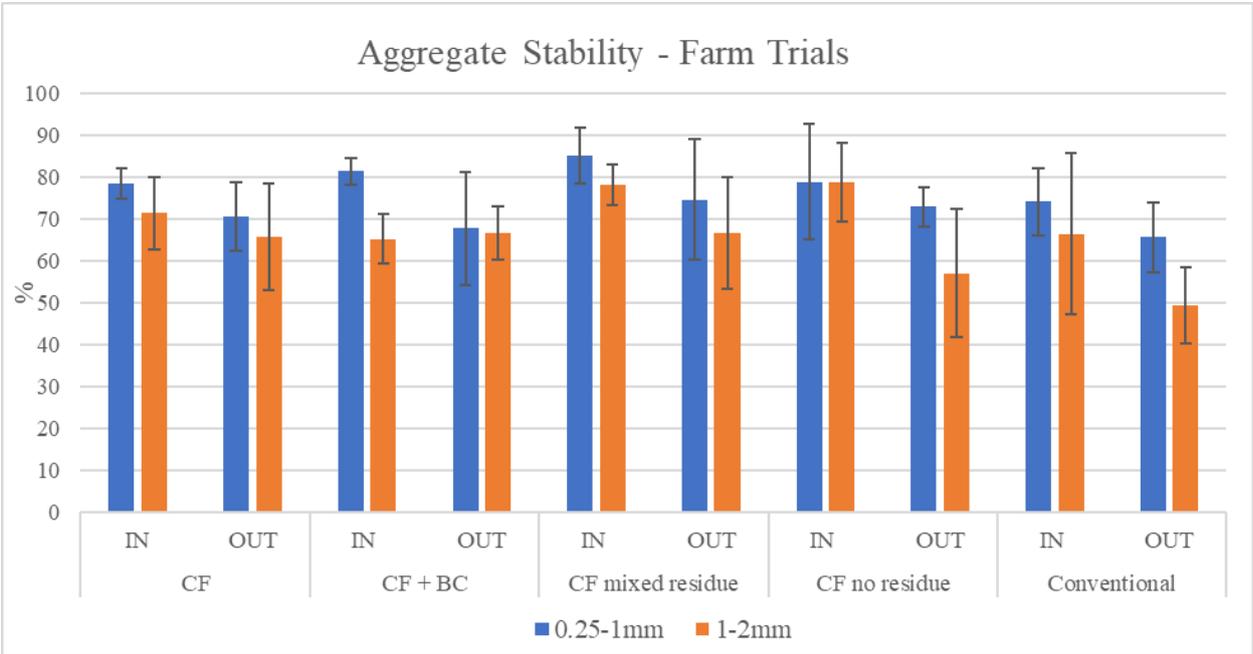


Figure 7: Aggregate stability (%) of farming trials for all five treatments, inside and outside planting basins. As conventional plots do not have basins “in” refers to sampling by planting stations, whilst “out” means between planting rows. The small fraction (0.25-1mm), and the larger fraction (1-2mm) are both graphed. Error bars are standard deviation, n=4.

Biochar Trial:

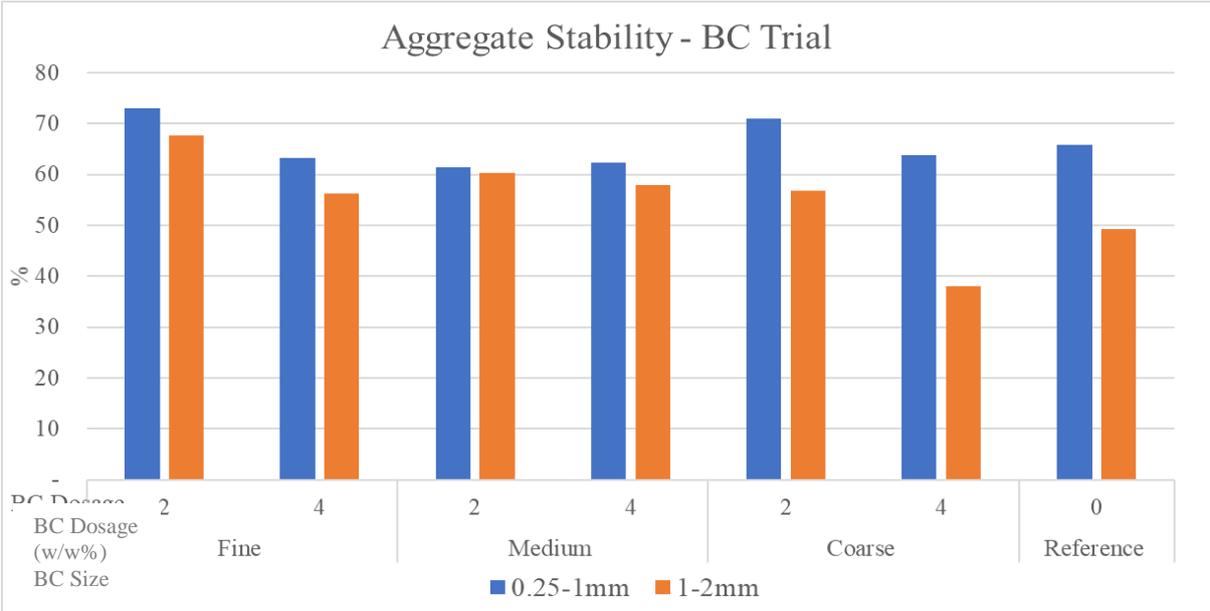


Figure 8: Aggregate stability (%) of BC trial graphed according to BC size, and dosage (w/w%). Both the smaller fraction (0.25-1 mm) and the larger fraction (1-2 mm) are included. Note: only one observation per trial, thus no standard deviation/error bars.

Soil aggregate stability varied between values of 50% up to values of 85% as illustrated in figure 10. The proportion of stable aggregates for the smaller size fraction, 0.25-1mm, has consistently and significantly higher values (65-85%) than those of the larger size fraction 1-2mm (40-80%). There is also a significant difference between inside and outside planting basins; where stability is higher inside basins for all treatments and both size fractions (figure 10). Conventional plots indicate lower values, with a combined average of 63%, whilst CF with mixed residue had the highest combined average of 73%. However, there were no significant difference between treatments.

For the BC trial (figure 11) there is no significant relationship between BC dosages or BC size fractions, the only significant difference was found between the aggregate size fractions; the smaller fraction is more stable, which was also found in the farming experiment. The BC trial in the farming experiment has overall higher values (40-85%) than what is found in the BC trial values of (38-73%).

pH and Total Organic Carbon :

Farm Trials:

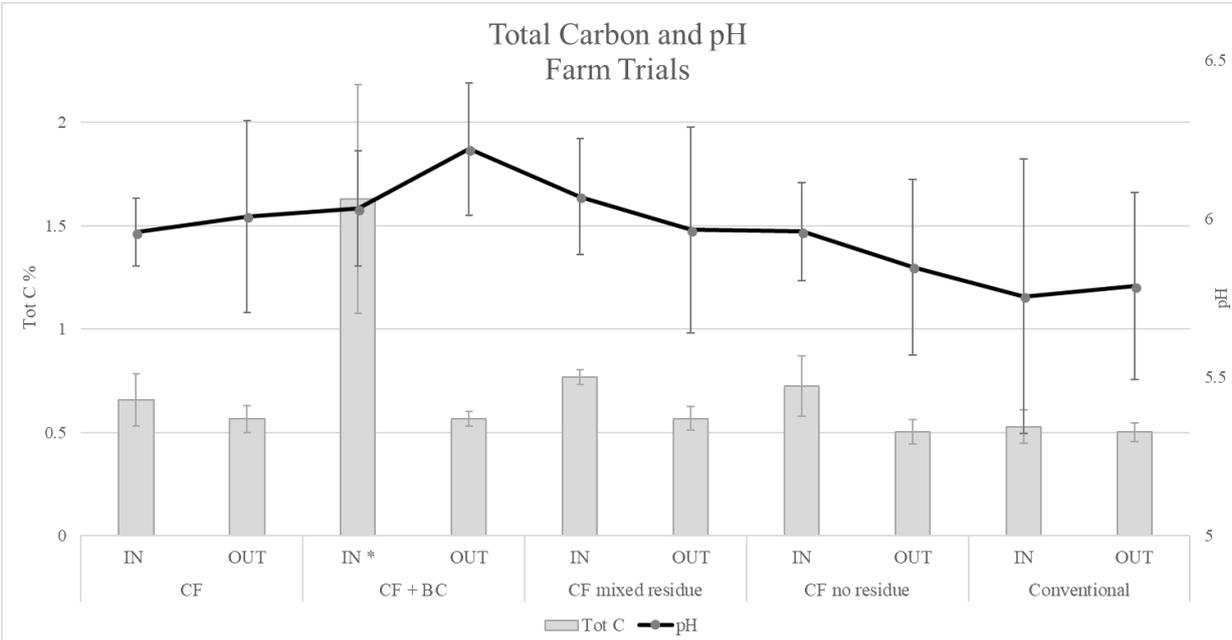


Figure 9: Total Carbon (%) and pH for farm trials. Includes five treatments inside and outside basins. Conventional plots do not have basins, “in” refers to sampling by planting stations, whilst “out” refers to sampling between planting lines. Standard deviation is illustrated as error bars, n=4.

*Significantly different at 95% accuracy (Total C)

There are no significant differences of pH between treatments, but TOC at the BC trials (inside basins) is significantly greater than the treatments without BC (figure 12). The treatment with BC added to basins has values three times that of the other treatments (1.6%), high values of TOC are expected considering the high carbon content of BC. On average inside basins compared to outside basins are significantly higher for both TOC and total nitrogen (appendix 2), but not for pH. Conventional plots indicate no difference in TOC between inside and outside, all other CF treatments do. If the BC treatment and the conventional treatment are removed the difference of TOC between inside and outside basins is still significant. indicating that there is an effect of CF basins, as well as BC on carbon content on the soil.

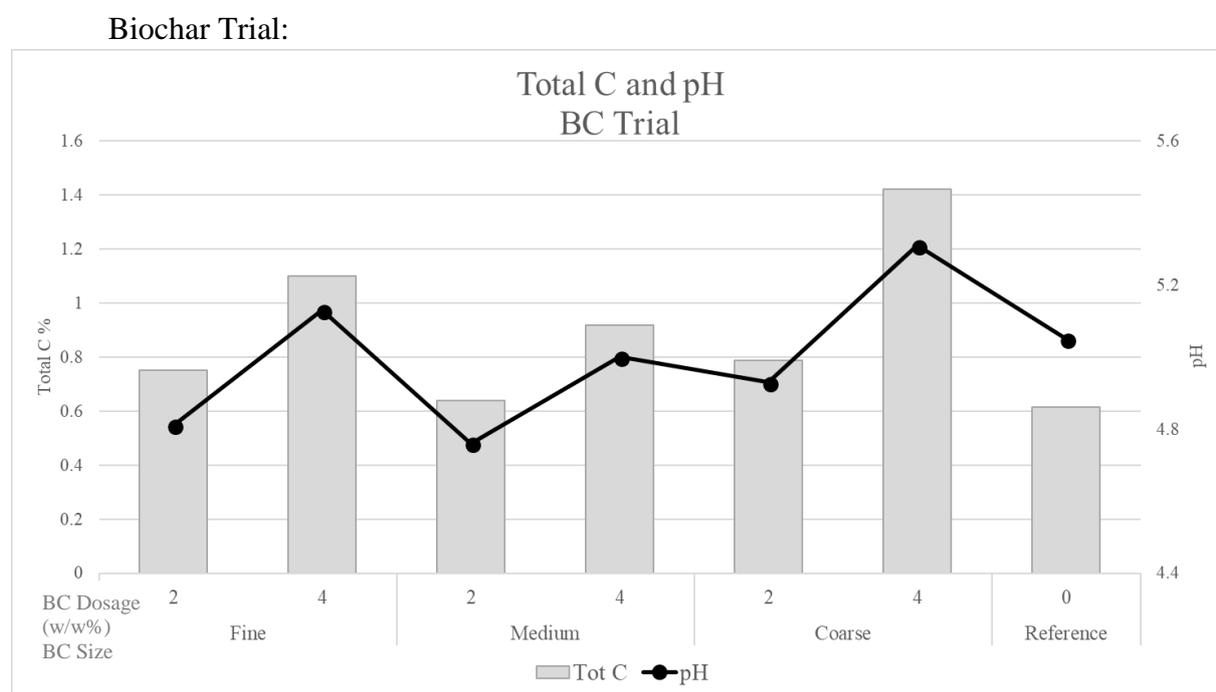


Figure 10: Total C (%) and pH of BC trials. Includes BC size and dosage (w/w%). No error bars as n=1.

In the BC trial no significant differences between dosage and size for TOC, nitrogen (appendix 2) or pH was found. There is indication towards higher TOC with increased dosage, but not for increased size (figure 13). The reference plot pH is higher than that of several samples with added BC, which is not expected. If the reference plot is not included there is a significant correlation between TOC and the pH ($R^2 = 0.97$, $p < 0.001$) illustrated in figure 14. If the reference plot is included R^2 becomes 0.70 ($p < 0.05$), still significant but less so.

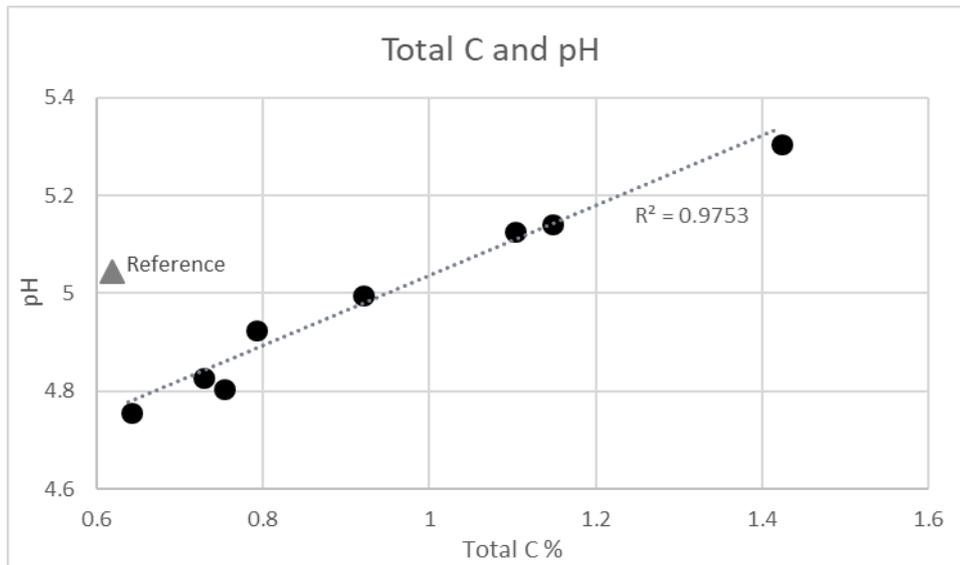


Figure 11: Correlation of Total C (%) and pH in the BC Trial. Reference plot is not included in line of best fit but is graphed as an outlier. $R^2 = 0.97$, $p < 0.001$. (with reference plot included: $R^2 = 0.70$, $p < 0.05$).

HWEC:

Farm Trials:

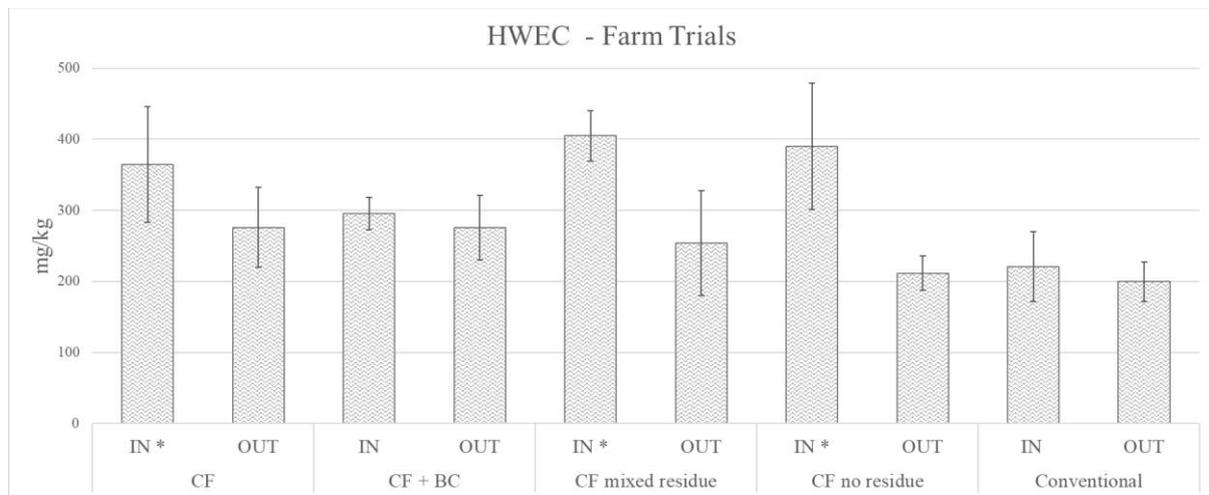


Figure 12: HWEC (mg/kg) of farm trials for treatments inside and outside basins, conventional plots do not have basins, so “in” refers to sampling by planting station and “out” refers to sampling outside the planting rows. Standard deviation is illustrated as error bars, $n=4$.

*=Indicates a significant difference to conventional treatment values. (90% accuracy)

As observed with TOC, HWEC also has a significant difference between inside and outside basins where HWEC is higher inside basins. If the conventional and BC treatments are removed, the significance of the difference between inside and outside basins increases. However, the BC plots do not show an increase in HWEC, which is in great contrast to the significant increase seen in SOC. There are differences between treatments (Figure 15), the

significant difference being found between conventional and CF with mixed residue (in), CF no residue (in), and CF (in).

Biochar Trial:

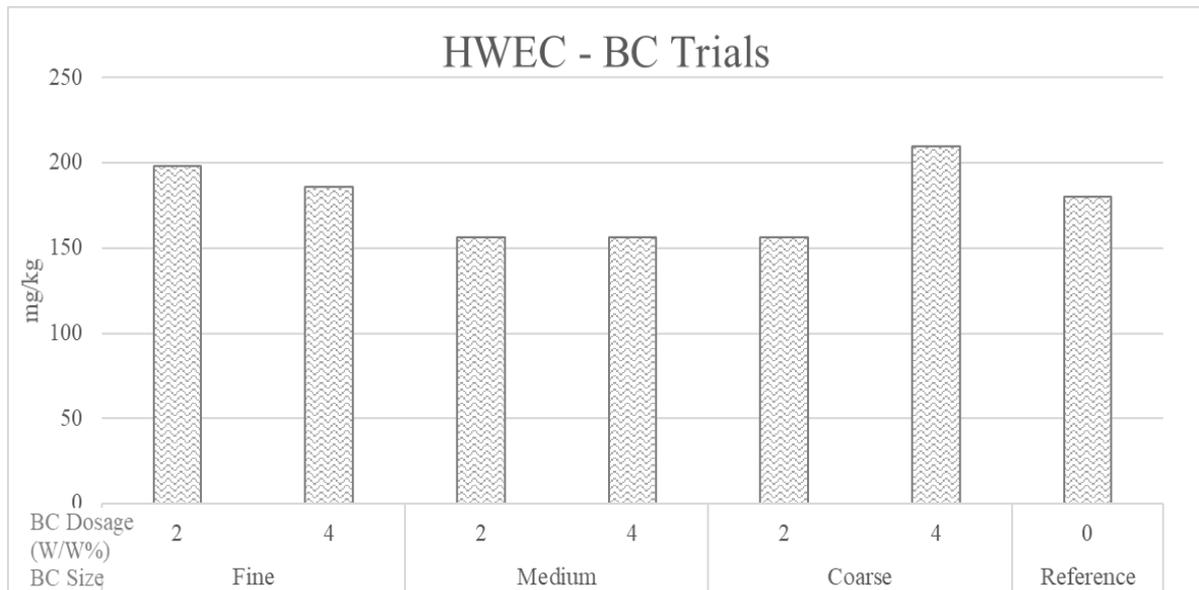


Figure 13: HWEBC (mg/kg) for BC trials, includes BC size and dosage (w/w%). Note: only one repetition, no standard deviation.

No differences between size and dosage are significant in figure 16. BC is not associated with increased HWEBC, supporting what was seen in figure 15. BC trial values are overall smaller (150-210 mg/kg) than those found in the farm trials (200-400mg/kg).

HWEC and SOC:

Farm Trials:

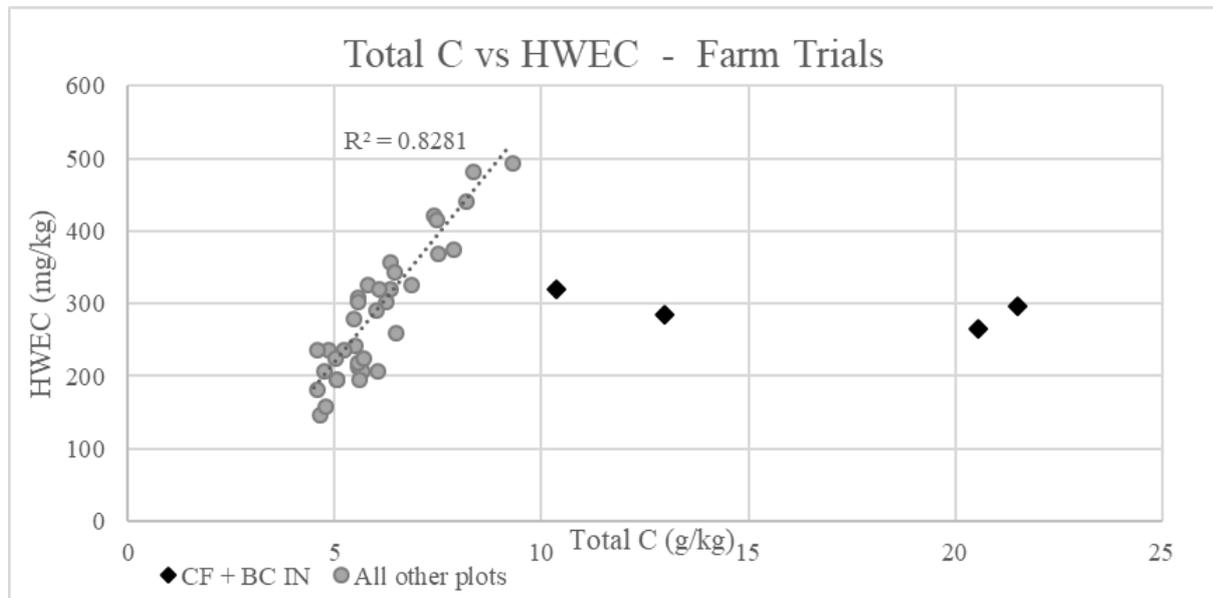


Figure 14: Correlation of total carbon (%) and HWEC on farm trial plots. values for CF+BC trial inside basins is excluded from line of best fit ($R^2=0.83$, $p<0.001$). If BC+BC inside is included in the correlation $R^2= 0.23$, $p> 0.05$.

The correlation of SOC with HWEC in figure 17 is highly significant ($R^2=0.83$, $p<0.001$) when data from CF +BC plot (inside basins) is not included. If this data is included the correlation is not significant ($R^2= 0.23$, $p> 0.05$).

Biochar Trial:

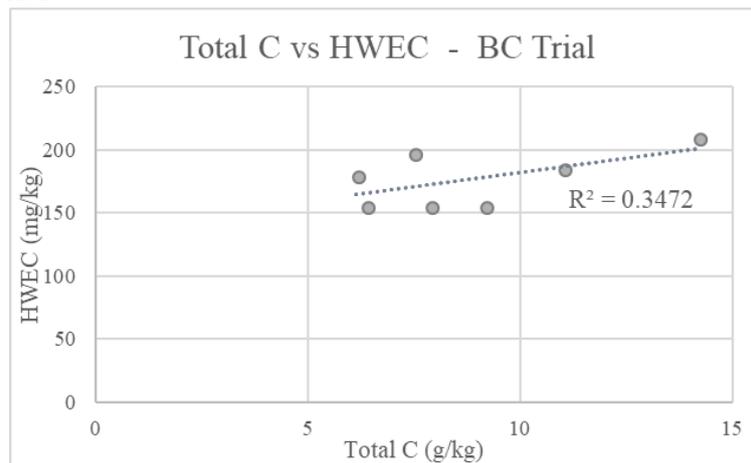


Figure 15: Total carbon (%) is graphed against HWEC (mg/kg) for BC trial values. Includes correlation coefficient $R^2=0.35$, $p>0.05$.

Biochar trial data correlates SOC with HWEC to a lesser extent than the farm trials (figure 18). The correlation ($R^2=0.35$, $p>0.05$) is not significant. This corresponds to the results found in the farm trials (figure 17), where BC amendment does not follow the relationship seen in soils without BC.

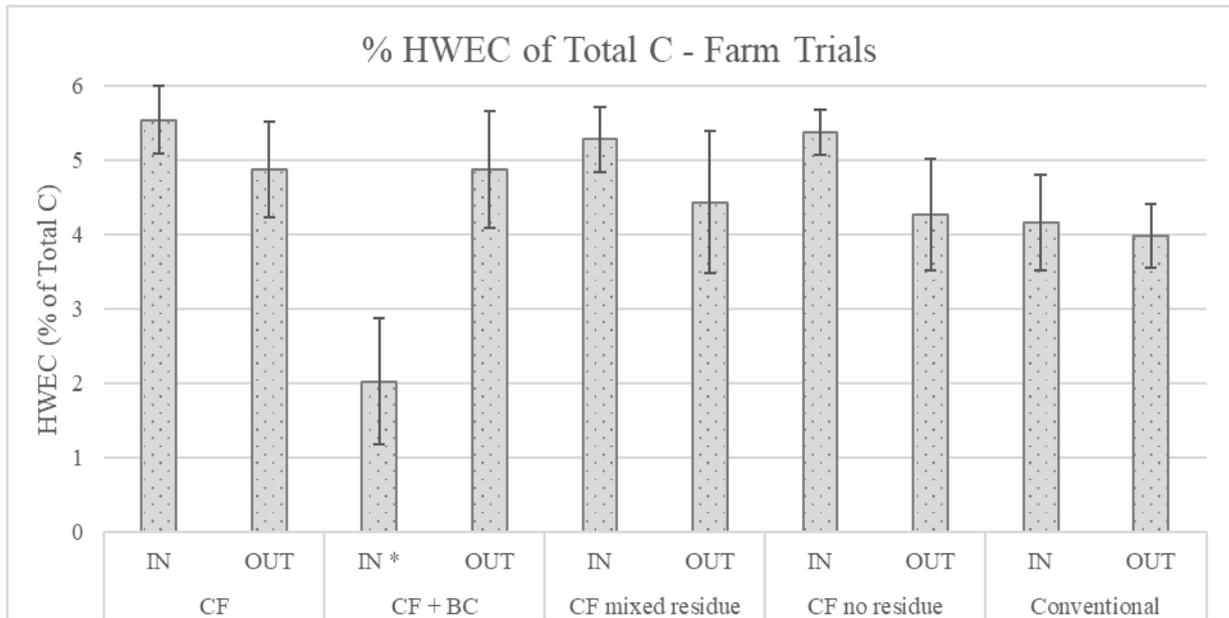


Figure 16: HWEC is presented as a percentage of total carbon. For farm trials. Conventional plots do not have basins, “in” refers to sampling by planting stations and “out” refers to sampling outside of planting row. Standard deviation is error bars, n=4.

*= Significant difference (90% accuracy)

Derived from figure 17, HWEC as a percentage of total carbon (Fig 19) indicates similar results. Where CF+BC inside basins do not follow the same relationship as CF plots; CF + BC (inside) is significantly lower than CF (in), CF mixed res (in), and CF no res (in).

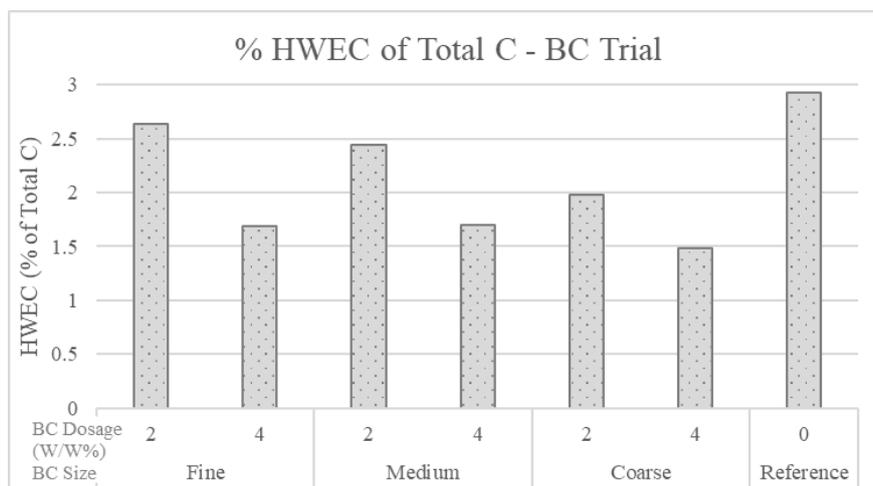


Figure 17: HWEC as a percentage of total carbon for BC trial. Includes BC size and dosage (w/w%).

As a percentage of total C HWEC values range between 1.5% and 3%, which is lower than farm trials which range between 2% and 5.5%. Values are highest in the reference plot of the BC trial (Figure 20), indicating a negative effect of BC of HWEC, smaller dosages indicate higher percentages, also indicating higher BC inputs decreases HWEC.

Discussion

SOC, Total N, and pH:

The SOC illustrated in figure 12 shows a significantly higher C content in the BC treatment, an increase in SOC in BC trials is expected due to the carbon rich nature of BC. An increase in CF trials compared to conventional plots is also expected, however differences between treatments are not significant but the difference between inside and outside basins is. CF trials (normal, with and without residue) did not vary significantly from each other indicating residue retention does not impact SOC significantly in this system. Studies such as Tirol-Padre et al. (2005) found increased SOC and nitrogen when residue management was used. Which contradicts this study, which show minimal differences between mixed residue and no residue, where the average for Tot N (appendix 2) was the same for both treatments, and the SOC average was a mere 0.06% greater for mixed residue than for no residue retention. Normal CF is like that of mixed and no residue, these results indicate no significant effect of residue retention in improving SOC or Tot N of soil.

However, the use of planting basins improved SOC and N of soil, where both C and N increased significantly inside basins. All CF treatments had a visible difference between in/out, whilst conventional plots did not vary between sampling inside and outside their planting row. Significance of TOC between in/outside of basins improved when conventional (showing no changes) and CF+BC (showing large differences) were not included. Highlighting the positive impact of basins on soil quality, reflected through C and N. Whether basins are the most effective choice to reduce tillage would still need further research, it would be of interest to see if rip lines present similar improvements to soil properties.

pH did not vary significantly between treatments or inside/outside basins, the maximum average was found for CF+ BC plots, and minimum in the conventional trial. Overall, the farm trial pH was relative uniform throughout the experiment. However, in the BC trial pH provided more distinct results. Figure 13 and 14 show a clear relationship between SOC and pH, where

increased carbon levels increased soil pH, thus indicating that BC increased pH. This result is expected, as it has previously been found in multiple studies (Martinsen et al. 2015, Cornelissen et al 2013). However, this study confirms a correlation between added BC and soil pH five years after BC application. This long-term impact was not found by Cornelissen et al (2018) in Indonesia, where the effect of BC faded after 3-5 years. The climate in Mkushi likely allows for long-term BC effects, as it is not washed away by heavy rains as was the case in Indonesia (Cornelissen et al. 201).

HWEC and SOC:

From figure 17 of SOC vs HWEC in the farm trials, there is a clear correlation of all values with the exception of those of the CF + BC plots inside basins. The plots with BC do not follow the same pattern, indicating that increasing SOC due to added BC does not increase HWEC. This is also seen in the BC trials where there is no significant relationship between the SOC and HWEC. BC clearly increases SOC (figure 12), but this carbon is not a part of the labile fraction of carbon associated with HWEC. Thus, the carbon is included in part of the stable soil carbon fraction. This agrees with the long-term carbon sequestration promoted through BC production (Cornelissen et al. 2013), where BC has been calculated to sequester more carbon than that associated with vegetation re-planting (Lehmann 2007).

The relationship between HWEC and SOC is further presented in figure 19 and 20 where the percentage HWEC of total C is significantly lower for the farm trial with BC addition than that seen in CF treatments. Low values are also observed in the BC trial, where all values with BC are lower than the reference plot.

A reduction in HWEC, the labile soil carbon, due to BC can have negative effects on soil properties. Low amounts of labile carbon will impact nutrient cycling by reducing nitrification and thus the availability of N for plants. Less labile C reduces microbial activity, which slows the mineralisation process which makes nutrients (such as nitrogen, potassium, and phosphorus) available for plant uptake (Chen et al. 2003). Biochar might incorporate large amounts of stable carbon to the soil, but not in a form which is positive for microbial activity and nutrient cycling.

Both these studies were conducted several seasons after BC was incorporated into the soil, and time will impact the BC effect on labile C and HWEC. The amount of decomposition, thus the loss of labile C is high in newly added fresh BC, such that the amount of labile C in BC reduces over time (Bruun et al. 2011). This relationship indicates that BC could have initially increased

HWEC, but the effect has reduced over time. The properties of BC will affect the amount of labile and SOC, this includes methods of pyrolysis (temperature) and type of feedstock. BC plots likely had initial high initial values of HWEC, which have faded over time altering the impact of BC on soil properties.

Soil C/N Ratio:

Nitrogen is a major nutrient needed for plant growth and is also linked to SOC. Nitrogen fertiliser is needed in CF, as minimal tillage is often related to initial low N availability, as microorganisms increase, nutrient recycling can also increase (Dordas 2015). Accurate use of all CF aspects, including increased SOM from residues, minimum tillage and, crop rotation with nitrogen fixing plants are needed for N to improve. When residue is added to fields, the input of SOC helps promote microbial growth. If there is not enough N to support the growth, N is taken from the soil and immobilised, until the carbon decreases, and the population of microbes is reduced, and N is released back to the soil (USDA 2018). Low N has also been found due to immobilisation by residues left as soil cover (Bradford and Peterson 2000). The balance of carbon and nitrogen (C/N ratio) is an important proxy for N availability in soils, with smaller values indicating greater N availability.

The carbon to nitrogen ratio (C/N) in the soil impacts the decomposition and nutrient cycling of soils and is therefore linked to residue retention (USDA 2018). When residue is initially added microbial activity increases to use readily available carbon, meaning nitrogen is of high demand and is not available to plants. As residues decompose over time, the C/N ratio decreases as respiration uses carbon, and nitrogen is used to build microbial cells (Brady and Weil 2014).

Table 1: Farm Trial Soil C/N Ratio

Treatment	Inside/Outside Basin	C/N
CF	IN	13.8 ± 3.5
	OUT	20.4 ± 7.8
CF + BC	IN	30.7 ± 7.9
	OUT	18.8 ± 3.4
CF mixed residue	IN	16.3 ± 1.2
	OUT	23.4 ± 4.2
CF no residue	IN	16.8 ± 5.0
	OUT	27.8 ± 20.0
Conventional	IN	14.9 ± 4.7
	OUT	17.1 ± 4.1

Table 1 documents the carbon to nitrogen ratio (C/N) derived for each treatment of the farm trials inside and outside basins and the subsequent standard deviation. No significant difference between treatments, or between in/out of basins.

One would expect lower ratios inside basins, as more roots and microbial activity (as seen in HWEC – figure 15) drives decomposition which increases the amount of N available to plants. Lower values inside basins are seen in table 1, however the difference between inside and outside basins is not significant, likely due to high variability. This could indicate basins improve nutrient availability and soil quality, as values are less pronounced in conventional plots without basins. The exception is clearly the BC treatment, where values inside basins are close to 30, due to large ratios associated with BC feedstock. This could further the argument that BC suppresses nutrient cycling, specifically N mineralisation, and availability, as seen with reduced HWEC values. This is further illustrated in Table 2, where the BC trials have, for the most part, higher ratios than the reference plot, and overall greater values (26-52) than the farm trials (14-30). Arable land usually has ratios between 8 to 15 in surface horizons (Brady and Weil 2014) which is lower than what was found in the Mkushi farm trials. Cornelissen et al. (2013) found C/N ratios over 40 in Mkushi with BC amendment. Such high C/N ratios might indicate trials with BC need more fertiliser to maintain a C/N ratio better suited for growth. The uncertainty of the C/N ratio is high due to low total N values bordering on the detection limit (DL = 0.01% Total N) of analysis.

Table 2: BC Trial Soil C/N Ratio

Size	Dosage w/w%	C/N
Fine	2	45.2
	4	52.4
Medium	2	26.3
	4	34.3
Coarse	2	44.5
	4	40.7
Reference	0	29.9

Table 2 includes the carbon to nitrogen (C/N) ratio for the BC trial. Note: no repetition; no standard deviation.

Aggregate Stability:

In the farm trials there is indication of lower aggregate stability in conventional plots (figure 10), however no treatment was significantly different. The treatment with CF and BC did not differ from the CF plots, indicating BC does not help increase aggregate stability. There is however, a significant difference between the stability inside and outside planting basins, showing that the use of planting basins is important for soil aggregation. The higher stability seen inside basins is connected to the plants and roots inside basins which increases the SOC

content, which is related to aggregate stability. Both the BC trial and farm trial had significantly more stable aggregates in the smaller fraction than in the larger aggregate fraction. The BC trial did not indicate an increase in aggregate stability because of increased BC dosage or BC size. This points towards BC not being the main factor driving soil aggregation in this system.

Aggregate Stability and HWEC:

The stability of soils is often related to the SOC, such that more carbon is related to a higher aggregate stability (Blume et al. 2016). HWEC is a proxy for microbial activity and the labile fraction of carbon in soil (Weigel 2011) and is therefore used to compare to the aggregate stability in figure 10 and 11.

For the BC trial the correlation of aggregate stability and HWEC (figure 22) was low ($R^2=0.06$, $p>0.5$) and indicates no significant correlation, which is the opposite of what is expected. Aggregate stability does not correlate significantly to SOC either ($R^2=0.38$, $p>0.05$), but more so than HWEC (figure 22). Therefore, we can conclude neither HWEC or TOC was responsible for the aggregate stability of the BC trial. For the farm experiment however, there is increasing stability with increasing HWEC (figure 21) with a strong significant correlation ($R^2=0.80$, $p<0.001$). These values are derived from multiple samples and is likely more accurate than that of the BC experiment. This result indicates improved aggregate stability with increasing HWEC. Both carbon content (SOC and HWEC) and stable aggregates increased inside basins in comparison to outside basins, driving the correlation seen in figure 21. Thus, we can say HWEC and aggregate stability have a positive relationship, whilst BC had no relationship with aggregate stability.

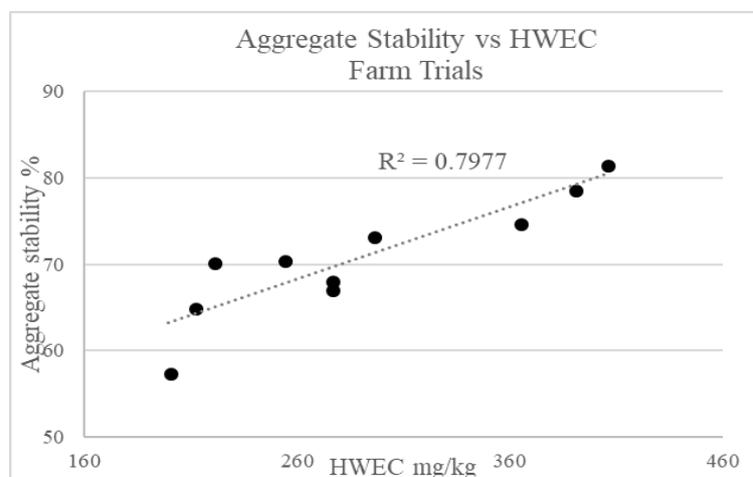


Figure 18: Correlation of aggregate stability (%) and HWEC (mg/kg) for farm trial, includes linear line of best fit: $R^2=0.80$ <0.001 .

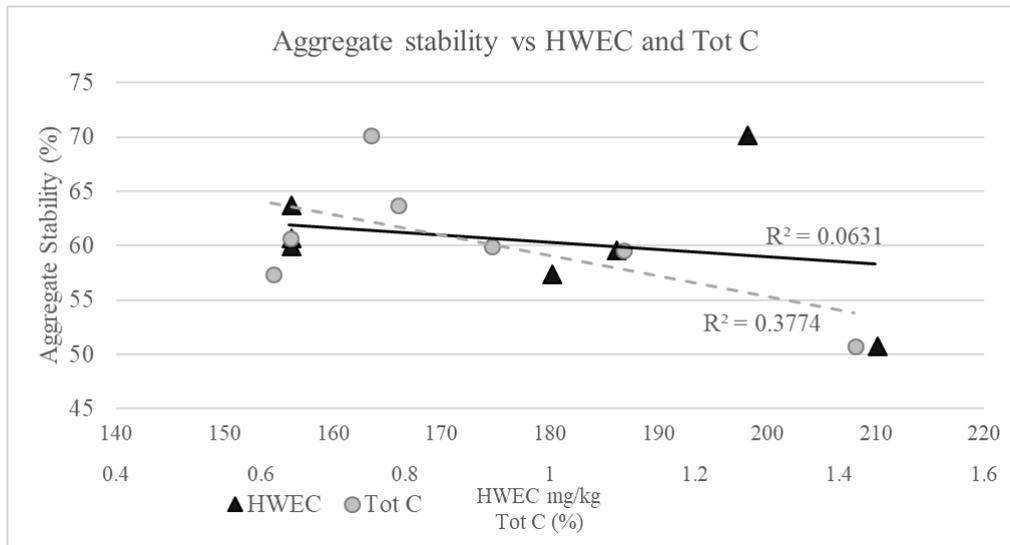


Figure 19: Aggregate stability (%) correlated to HWEC (mg/kg) and TOC (Tot C%). Correlation with HWEC ($R^2 = 0.06$, $p > 0.05$) and TOC ($R^2 = 0.38$, $p > 0.05$).

Long-Term Effects of Biochar on Aggregate Stability:

Results show that HWEC impacts aggregate stability with positive significant correlations, whilst BC does not. This is contradictory to previous studies (Cornelissen et al. 2013, Obia et al 2016) which found positive correlations between BC amount and increasing aggregate stability at the trials in Mkushi.

In Obia's (2016) study, optimum BC increased stability from 25 to 35 % for the 0.6-2mm fraction, and from 35-45% in the 2-6mm fraction two years after application. Obia et al. (2016) used a rainfall simulator to determine aggregate stability. In my study one would hypothesise to see similar results of increased stability due to BC in the soil. However, differences in methodology between the two studies adds uncertainties that need to be considered, this includes a difference in aggregate fractions used; the rainfall simulator uses overall larger aggregate fractions (0.6-2mm and 2-6mm), than the wet sieving method used in my study (0.25-1mm and 1-2mm). To compare results, we use the assumption that results derived from the wet sieving method will be approximately 21% higher (Grønsten and Børresen 2009) than those derived from a rainfall simulator. In addition to method, time is also an important difference between the two studies. Obia et al. (2016) analysed BC dosage one and two years after BC application, my study follows up five years later. Over time the amount of HWEC in BC will reduce (Bruun et al. 2011), which as discussed earlier, will impact aggregate stability negatively.

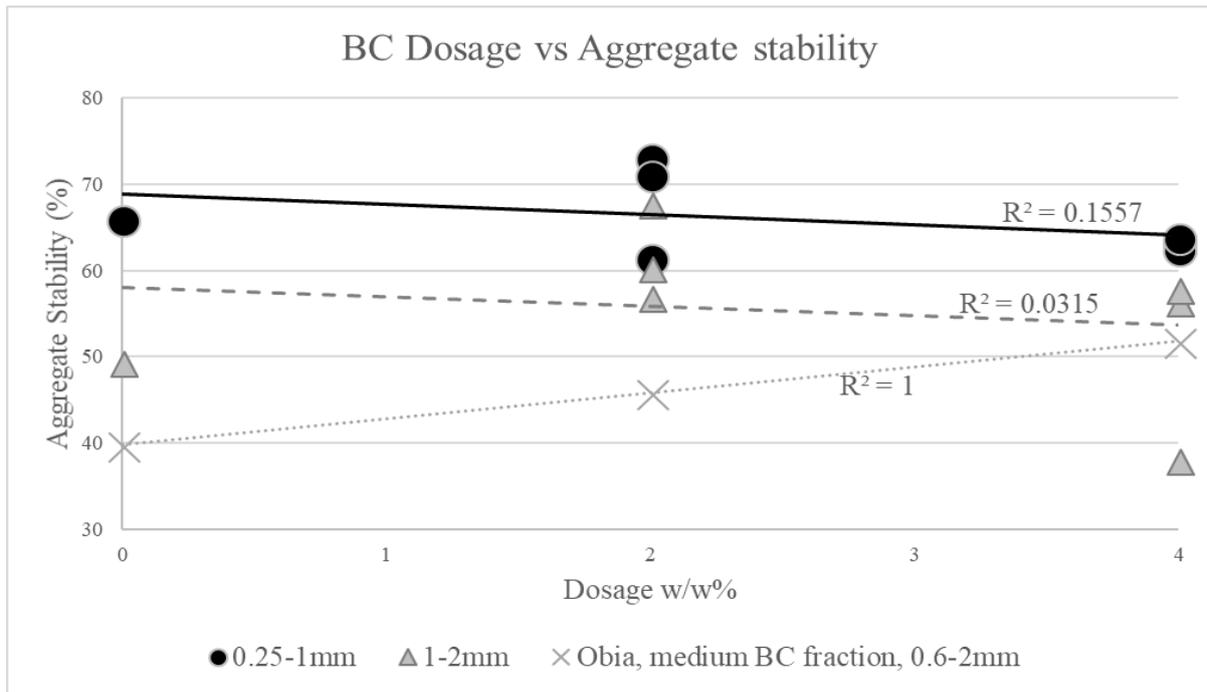


Figure 20: Dosage of BC (w/w%) graphed against aggregate stability (%) for BC trials. Includes results from Obia et al. (2016) of the medium BC fraction and 0.6-2mm aggregate fraction, which increases aggregate stability with 3% (± 1.4) for each % BC. Values are adjusted for difference in method (+21% as found in Grønsten and Børensen (2009)). 0.25-1mm fraction: $R^2=0.16$, $p>0.05$, 1-2mm fraction: $R^2=0.03$, $p>0.05$

Data from Obia et al. (2016) one year after BC amendment, found that aggregate stability increased significantly with BC dosage in the medium BC size fraction. The medium fraction is graphed using the values of aggregate stability derived from the positive correlation; values increases with 3% for each % BC added. Initial value is 18.8% + 21% to account for different methods (Grønsten and Børensen 2009). In contrast from the significant increase Obia et al (2016) found, my study found no correlation between dosage and aggregate stability (0.25-1mm fraction $R^2=0.16$, $p>0.05$, 1-2mm fraction: $R^2=0.03$, $p>0.05$) (figure 23). Thus, the significant correlation of BC and aggregate stability found one year after application, is not found five years later.

Values from two years after application by Obia et al. (2016) showed minimum values of 25 and 35%, and maximum of 51 and 41% (for fractions of 0.6-2mm and 2-6mm) by adding 21% to this studies values, we remain within a range similar to that found in my study (38-74%). However, the positive relationship between BC and improved aggregate stability also found two years after application in Obia et al. (2016) is not found in my study (figure 11 and figure 23). The results show no significant differences between the reference plot and those with added BC, some plots even have a lower stability with added BC. These results question the findings

of Obia et al. (2006) which concluded that BC causes improved aggregate stability, whilst my results from 5 years after BC application indicate that labile C (HWEC) causes increased aggregate stability, not BC.

The results of the BC trial have some uncertainties, specifically when looking at the reference plot. The reference plot is not significantly lower with respect to aggregate stability, SOC, or pH indicating there is some sort of error associated with this study. This could be due to an overall loss of BC over time, BC was added 5 years ago, and all values of SOC are lower now than what was presented by Obia et al (2016) at the start of the experiment. Alternatively, BC could have been lost by lateral transport, which was found to be of greater importance than vertical transport (Obia et al. 2017). This may cause movement of BC into neighbouring reference plots by surface erosion, increasing reference values to levels higher than what is expected. A third alternative is uncertainties associated with sampling and analysis. There is a possibility of having a subsample without BC present, or less BC than is representative of the plot, causing uncertainties like that of high dosage coarse BC showing the lowest aggregate stability. There is also uncertainty associated with a lack of repetition for the BC Trial.

Farm Trial vs BC Trial:

The results have consistently produced differences between the two experimental sites studied. The farm trial had overall higher values of HWEC, aggregate stability, and lower values of total C, pH, and greater C/N ratios. The BC clearly impacts the TOC content and the C/N ratio, whilst the other parameters indicate overall poorer soil quality in the BC trial. Both soils are Acrisols, but the site of the BC trial is on a loamy sand whilst the farm trials are located on sandy loam soil. The texture of soil is very important in determining its quality. Sandy soils are comprised of less clay, which is an important factor in both soil aggregation and chemical properties (CEC and pH); less clay means poorer soil quality (Brady and Weil 2009). Sandy soils are also more sensitive to erosion, and their quick draining ability results in a low water holding capacity. However, sandy soils are often related to taking better to CF and BC practises, and significantly improving soil properties such as water holding and CEC (Cornelissen et al. 2013). So, one would assume the BC trial would be more susceptible to changes, and improvements due to BC, but this was not seen.

Comparisons to Other Studies – Farm Trials:

The farm trials have been an active area of research since the first season in 2015. Several studies have measured soil properties such as pH, Tot C, Org C, and Tot N, which can be compared.

Table 3: Comparing data of farm trials to background data, past studies, and unpublished data from 2018.

Soil Property	Background soil data 2015 (Martinsen, unpublished data 2018)	2016 (Obia et al. 2016)	2016 (Aas 2016)	2017 September	2018 Jan/Feb (SOC: Phiri and Kabwe 2018) (Tot C: Martinsen, unpublished data 2018)
pH	pH (CaCl ₂) In: 6.3±0.15 Out: 4.95±0.37	pH (H ₂ O): 6.4	pH (H ₂ O) CF: 6.38±0.31 CF+BC: 6.57±0.14 Conv: 5.51±0.25	pH (H ₂ O) In: 5.96 ± 0.24 Out: 5.97±0.30 Avg: 6.0±0.23 CF: 5.96 ±0.12 CF+BC: 6.03±0.18 Conv: 5.76±0.43	
Total C %	In: 0.74±0.06 Out: 0.57±0.08		CF: 0.66±0.11 CF+BC: 1.67±0.44 Conv: 0.58±0.08	IN: 0.86±0.47 OUT: 0.54±0.06 Avg: 0.7±0.37 CF: 0.66±0.13 CF+BC: 1.62±0.55 Conv: 0.52±0.08	IN: 0.69±0.41 OUT: 0.45±0.08 Avg: 0.6±0.35 CF: 0.59±0.17 CF+BC: 1.24±0.66 Conv: 0.47±0.08
Organic C %	In: 0.58±0.07 Out 0.44±0.06	0.67			IN: 1.07±0.24 OUT: 0.77±0.17 Avg: 0.88±0.90 CF: 1.07±0.19 Conv: 0.84±0.23
Total N %	In: 0.03±0.01 Out: 0.02±0.01	0.01	CF: 0.06 ±0.01 CF+BC: 0.07±0.01 Conv: 0.05±0.01	IN: 0.05±0.02 OUT: 0.03±0.01 Avg: 0.04±0.02 CF: 0.05±0.03 CF+BC: 0.06±0.02 Conv: 0.04±0.01	IN: 0.04±0.02 OUT: 0.03±0.02 Avg: 0.04±0.02 CF: 0.04±0.02 CF+BC: 0.06±0.01 Conv: 0.04±0.01

Table 3 includes three past studies and unpublished data from 2018, with the intention of comparing to results from this study. pH, total C, organic C, and total N are presented along with the standard deviation (if available). Data includes results from 3 main treatments, inside and outside planting basins, and an average (avg).

Data from Aas (2016) is presented from inside basins, thus also data from this study (2017) and from 2018 are presented for inside basins to compare for CF, CF+BC and Conv. Obia et al (2016) data is also from inside basins. 2017 data is averaged for all treatments for inside and outside basins, to compare to 2015 background data. The method used to calculate pH, either H₂O or CaCl₂, is shown for each study.

pH:

The change in pH over two to three years is most interesting when comparing inside versus outside basin measurements. Assuming conversion between pH measured in calcium chloride (CaCl_2) and water (H_2O) are approximately that of $\text{pH}(\text{H}_2\text{O}) = 0.6 + \text{pH}(\text{CaCl}_2)$ (Brennan and Bolland 2008) pH inside basins have decreased over time whilst outside have increased. Thus, eliminating the significant difference between inside and outside found in 2015 (figure 24). The pH inside/outside from 2015 proved significantly different whilst data from 2017 did not (appendix 1) (figure 25). The pH normalising towards similar values across the entire plot indicates that the effect of initial liming has worn off, liming was last done in 2014 inside basins, which caused the difference seen in figure 25. Liming will likely be needed to be repeated in the near future to increase the pH.

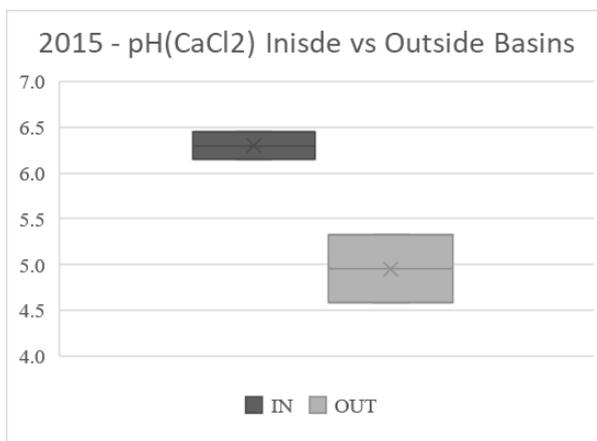


Figure 21: Box plot of pH inside and outside basins for 2015. Graph values are derived from average values and standard deviations (as seen in table 3).

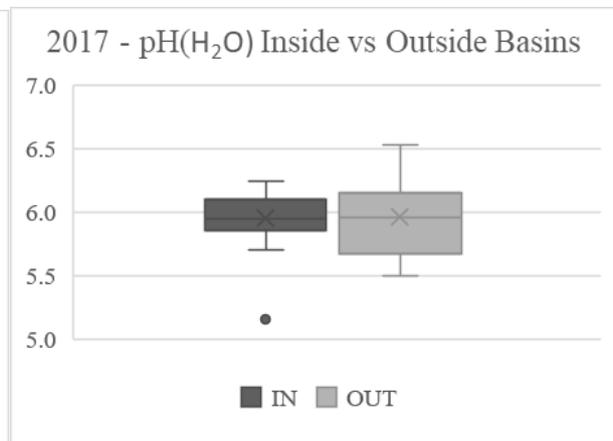


Figure 22: Box plot of pH inside vs outside basins for 2017. Values from all treatments are used.

Total Carbon:

Total carbon has remained consistent from year to year, and over the seasons. All studies indicate higher carbon inside basins than outside, and all indicate higher carbon in BC treatments. Since 2015 there has been a slight decrease in Tot C for all treatments, it is of interest to see if a reducing trend continues. We hope to see increases in C for CF and BC treatments, and decreasing values in conventional treatments. Here values of C decrease for BC, which could indicate a reduction in the effect of BC, CF also doesn't increase in Tot C over time. These changes in Tot C are too small to make any concrete conclusions, longer term data is needed. All values for Tot C are derived using the same methodology such that comparisons can be made accurately.

Organic Carbon:

The same pattern is seen in Org C, where inside basins, and treatments with CF have higher values. For Org C the values have increased between 2015 and 2018, however this comparison is difficult to make due to the variation in methodology. 2018 values of Org C are found to be higher than Tot C in the same samples, this is not possible, the data from 2018 of Org C is too high, a result of the Walkley-Black method used.

Total Nitrogen:

Total nitrogen is consistent over time, showing no changes greater than 0.02%. This further reflects that the C/N ratio is controlled by the input of carbon.

The study done in 2016 on the farm trials by Aas, found similar results to this study, including increased TOC and C/N ratio in CF+BC plots. Additionally, an increase in CEC was found in CF+BC and CF plots compared to conventional, and an overall high nitrification rate. Overall BC in combination with CF did not improve soil nutrients more than CF itself, which could be related to the results seen in my study of reduced labile C with BC addition. These studies indicate BC can reduce the labile C fraction such that nutrient cycling is suppressed and reduces nutrient availability in the soil.

Seasonality of HWEC:

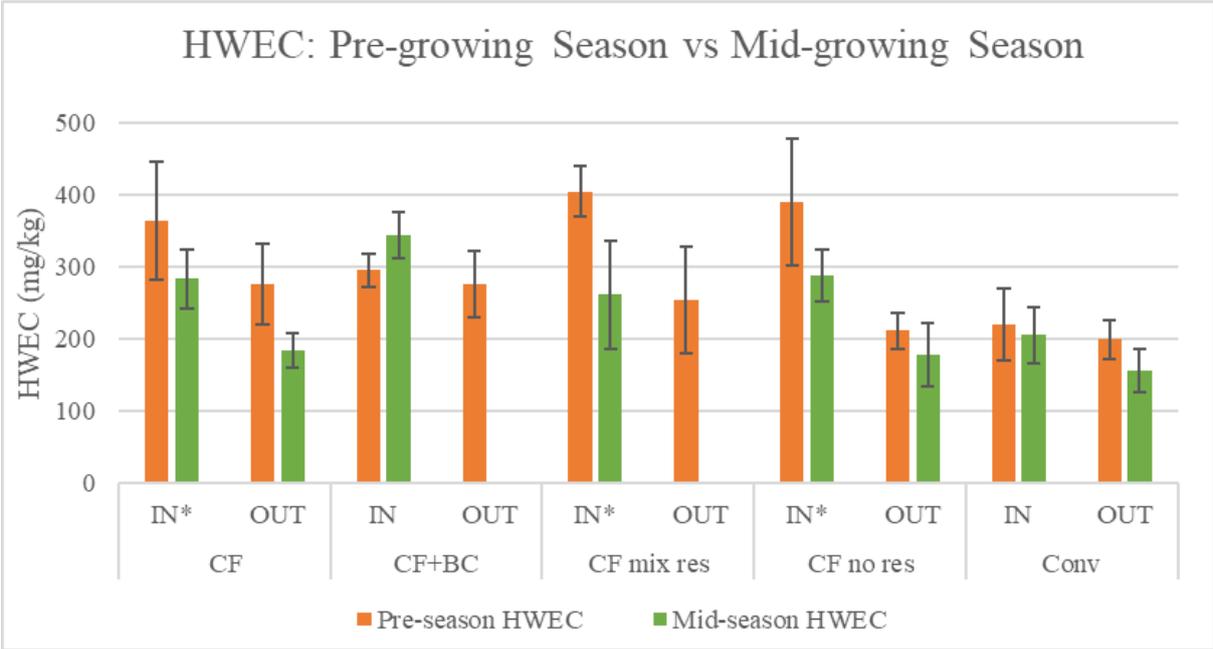


Figure 23: HWEC (mg/kg) in September 2017 (pre-growing season - dry season) and HWEC from February 2018 (mid growing season - wet season). Unpublished results from Echeverri, J. L. M. 2018. Data includes standard deviation as error bars.

*=2017 pre-season data is the same of figure 15, such that significant differences were found between CF(in), CF mix res (in), and CF no res (in) compared to conventional.

The seasons pictured in figure 2 (dry and hot season) and figure 3 (warm wet season) are compared. Due to the rapid response of labile carbon, we can compare the HWEC between seasons to observe short term changes. In the CF trials (CF, CF mixed residue, and CF no residue) the HWEC is greater before the growing season than during (figure 26). This indicates that the labile carbon fraction during plant emergence is being used and decomposed by increased microbial activity. Such that decomposition is greater than the input of SOC. The BC plot reflects the opposite, where mid-season labile carbon is higher, indicating less microbial decomposition than in the CF based plots. The conventional plot has no major variations between the seasons or use of planting basins. HWEC is a useful study to see short term changes in the carbon pool.

Possible Improvements to Study

The main source of uncertainty in the BC trial is the lack of repetitions in sampling. There should be taken multiple samples, such that an average and a standard deviation can be acquired, this will improve the accuracy of the results. This is especially important for such studies, where samples can include very different amounts of BC from the same plots. Another concern arises during pre-treatment where sieving through 2mm grates meant that the coarse fraction was broken apart, resulting in increased amounts of ash. This can impact the results of both physical and chemical analysis.

Further research into the labile fraction in BC, and the effect of fading over time is of interest to determine if the relationship of BC on aggregate stability (Obia et al. 2016) was a result of HWEC associated with fresh BC. Such that further conclusions can be drawn on the causes of aggregation in soil. Also, further investigation into the impacts of BC on soil properties, such as N mineralisation. To determine whether BC amendment can be negative for labile C and soil quality, and how these compare to positive aspects.

Further analysis into soil carbon and its processes could be undertaken by determining further carbon fractions. Analysis of SOC by methods such as dry combustion (Santi et al. 2006) or the Walkley & Black method (Blakemore et al., 1972), and analysis of Soil Inorganic Carbon by Pressure-Calcimeter methods (Sherrod et al. 2002) could be of interest. Increasing the scale of the analysis to include depth relationships could also present viable information of the impact of CF and BC. As changes are mostly found in the topsoil, the transportation and stratification at soil depth of both SOM (Franzluebbbers 2002) and BC are of increasing interest.

Conclusion

Supporting & Disproving the Hypotheses:

Hypothesis 1 through 5 were derived from knowledge of CF and BC, and the results of previous studies in the same region. The results of this study provide support for some hypothesis, whilst disproving others. The hypothesis and their relevant results are described below.

1. CF practices result in improved soil properties than conventional practices.
 - Indication of increased aggregate stability.

- Significantly higher HWEC in CF treatments (CF, CF with residue, and CF without residue all inside basins).
 - Significantly higher TOC in CF+BC plots, result of BC not CF.
2. We expect the use of planting basins to increase carbon content and HWEC:
 - Planting significantly improved aggregate stability, Tot N, SOC, and HWEC.
 3. BC is positively linked to aggregate stability, pH, and the carbon content of soil as documented by previous studies:
 - BC did not correlate to aggregate stability, but HWEC did. Indicating HWEC is a more important aspect in aggregation than BC. Asking the question of whether it is the labile C in fresh BC that is the reason for the improved aggregation found in past studies (Obia et al. 2016).
 - BC correlated significantly to pH in the BC trials.
 - The farm trial had significantly higher SOC due to BC, but not higher labile C (HWEC). Labile C was significantly reduced in treatments with BC in the farm trials, could indicate reduction in nutrient availability due to BC.
 4. Improvement of soil quality in CF plots, but not in conventional plots since start of the experiment in 2015.
 - Consistent values of Tot C, SOC, and Tot N over the 3 years.
 - pH has reduced inside basins, such that a significant pH difference is no longer seen between inside and outside basins.

This study found no significant differences between the five treatments in the farm trial, the exception being higher SOC in BC trial (inside), Such that improvement due to CF was only seen by significant difference between inside and outside basins. All soil properties, with the exception of pH, improved significantly inside planting basins. Basins act as one possibility of minimum tillage, research into how other methods, such as rip lines, improve soil properties in comparison would be a future topic of interest.

The BC trial did not find any significant relationships with the size and dosage of BC or any positive impact on the conventional farming practises represented in the reference plot. However, it did indicate long term effects on pH, such that even after 5 years pH correlated to SOC.

Labile C (HWEC) increased under CF, and decreased with BC, indicating the increase in SOC due to BC is not labile. This further indicates that BC could be negative for soil properties by

suppressing labile C, and its associated processes of mineralisation and nutrient cycling. The results also indicate that HWEC improves aggregate stability, whilst BC does not. These findings question the results found by Obia et al. (2016) which clearly indicate that increased BC improves aggregate stability. This further raises the question about the difference in HWEC in fresh BC and BC that has been in the soil for several years. Fresh BC has a higher HWEC content, which can be the reason behind the correlation of fresh BC and aggregate stability. The specifics of how HWEC changes in BC over time, and whether it negatively effects soil quality are valid topics of future research.

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Figure 2: Photo taken during sampling by NGI, September 2017.

Figure 3: Photo taken by Ellingsen, E. T. February 2018.

Figure 4: Photo courtesy of Talmo, I. K. February 2018.

Figure 5: Map from Sichinga, S. 2015. Presentation on “priorities for the management of soil in Zambia” from The African Soil Partnership consultation workshop, image originally from FAO, CFA, Zambia Branch homepage. Available at <https://www.slideshare.net/FAOoftheUN/zambia-53017346>

Figure 6: Experimental setup, courtesy Martinsen, V.

Figure 7: Photos courtesy of Talmo, I. K. January 2018.

Figure 8: Photo from CFU Zambia. Available at <https://conservationagriculture.org/gallery>

Figure 9: BC Trial setup. Photo Courtesy of Martinsen, V. 2013.

Figure 10 -26. All figures created by Ellingsen, E. T.

Appendix

Appendix 1: Statistical Analysis

Farm Trials:

Table 4: Summary of statistical analysis done, and critical values found of farm trial data.

Soil Property	Analysis of	Statistical method	Critical values
Aggregate stability	Treatments	ANOVA	F=2.16, F-crit=2.49
	In vs outside Basins	t-Test	t-Stat=4.00, T-crit=1.99
	Aggregate fractions	t-Test	t-Stat=2.96, T-crit=1.99
pH	Treatments	ANOVA	F=2.23, F-crit=2.64
	In vs outside Basins	t-Test	t-Stat=-0.12, T-crit=2.03
Tot N	Treatments	ANOVA	F=0.43, F-crit=2.64
	In vs outside Basins	t-Test	t-Stat=4.51, T-crit=2.05
Tot C	Treatments	ANOVA	F=4.13, F-crit=2.64
	Treatments	Tukey HSD	Tukey statistic= 8.93
	In vs outside Basins	t-Test	t-Stat=7.99, T-crit=2.09 For 3x CF treatments: t-Stat=4.60, T-crit=2.10
HWE C	Treatment	ANOVA	F=7.19, F-crit=2.21
	Treatments	Tukey HSD	Tukey statistic=100.63
	In vs outside Basins	t-Test	t-Stat=3.94, T-crit=2.04 For 3xCF treatments: t-Stat=5.44, T-crit=2.08
Tot C vs HWE C	Correlation	R ²	Excluding CF+BC (in): R ² =0.83, p<0.001 Including CF+BC(In): R ² = 0.23, p<0.05
Aggregate Stability vs HWE C	Correlation	R ²	R ² =0.80 p<0.01
C/N	Treatments	ANOVA	F=2.02, F-crit=2.21
	In vs outside Basins	t-Test	t-Stat=-1.09, T-crit=2.03

Statistical method includes one-way analysis of variance (ANOVA) (95% accuracy), two-tailed t-Test Assuming Unequal Variances (95% accuracy), and Tukey's Honest Significant Difference test (90% accuracy). Data which proved significant is shaded.

Tukey test uses the Tukey statistic (formula 2), to determine if the difference in means (M1-M2) is significantly different over a large dataset.

$$Tukey\ statistic = Tukey\ critical\ value * \sqrt{\frac{MSW}{n}}$$

2

Where the critical value is derived from multiple range test table (Harter 1960), MSW is “mean square within” derived from ANOVA test. N is the number of samples within data set. If the difference in means is greater than the Tukey Statistic the difference is significant. This was done for all analysis that proved a significant variance by an ANOVA test.

Biochar Trial:

Table 5: Summary of statistical analysis and critical values for BC trial data.

Soil property	Analysis of	Statistical method	Critical values
Aggregate stability	Size	ANOVA	F=0.64, F-crit=3.71
	Dosage	ANOVA	F=2.93, F-crit=3.98
	Aggregate fractions	t-Test	t-stat=-2.70, T-crit=2.3
pH	Dosage	ANOVA	F=4.72, F-crit=6.94
	Size	ANOVA	F=0.41, F-crit=9.28
Tot N	Dosage	ANOVA	F=1.56, F-crit=6.94
	Size	ANOVA	F=0.47, F-crit=9.28
Tot C	Dosage	ANOVA	F=4.98, F-crit=6.94
	Size	ANOVA	F=0.65, F-crit=9.28
Total C vs pH	Correlation	R ²	With ref: R ² = 0.70, p<0.05 Without ref: R ² = 0.97, p<0.001
Total C vs HWEC	Correlation	R ²	R ² =0.35, p>0.05
HWEC	Dosage	ANOVA	F=0.23, F-crit=6.94
	Size	ANOVA	F=0.92, F-crit=9.28
Aggregate stability vs HWEC	Correlation	R ²	R ² = 0.06, p>0.05
BC dosage vs aggregate stability	Correlation	R ²	0.25-1mm fraction R ² =0.16, p>0.05 1-2mm fraction: R ² =0.03, p>0.05
Aggregate stability vs Tot C	Correlation	R ²	R ² =0.38, p>0.05

Statistical method includes one-way analysis of variance (ANOVA) (95% accuracy), two-tailed t-Test Assuming Unequal Variances (95%accuracy), and Tukey’s Honest Significant Difference test (90% accuracy). Data which proved significant is shaded.

Appendix 2: Additional Data: Total Nitrogen.

The following values are discussed and used in deriving the C/N ratio seen in table 1 and 2, and averaged values of tot N for 2017 seen in Table 3.

Table 6: Total nitrogen (%) of farm trials

Treatment	Basins	Tot N (%)
CF	Average	0.042
	IN	0.053
	OUT	0.031
CF + BC	Average	0.043
	IN	0.055
	OUT	0.031
CF mixed residue	Average	0.036
	IN	0.047
	OUT	0.025
CF no residue	Average	0.035
	IN	0.047
	OUT	0.024
Conventional	Average	0.034
	IN	0.038
	OUT	0.031

Table 7: Total nitrogen (%) in BC trial.

Size	Dosage (w/w%)	Tot N %
Fine	Average	0.0188
	2	0.0166
	4	0.021
Medium	Average	0.0255
	2	0.0243
	4	0.0267
Coarse	Average	0.0263
	2	0.0177
	4	0.0349
Reference	0	0.0206



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