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Effects of Biochar and Pigeon Pea on Soil Nitrogen and Soil Carbon in Chipata and Mambwe, Zambia

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Environmental and Natural resources

Abstract

Plant needs sufficient nutrients to grow. Sub-Saharan Africa is experiencing a critically negative nutrient balance, and nutrient input from fertilizer and mineralization of organic matter is smaller than nutrient output as harvested crops, leaching and erosion. Witch increasing difficulties in the food production systems, there is a need to adapt management practices that increase the soils health and fertility. Conservational agriculture (CA) is one such farming system that uses novel technology and aims to be a sustainable, resource-saving agricultural production system that intensifies production and produces higher yields through three main principles. These are minimal soil disturbance (minimum tillage), crop rotation, and permanent residue cover, together with integrated weed management. Biochar is often done in addition to CA. This is so that the soils carbon content could potentially increase. Rotetation with pigeon pea is quite common in easter Africa, wharea as it is a new management practice in Zambia. Pigeon pea is nitrogen fixating, and there is a hope to increase both soils nitrogen content and plant available N.

The first cropping season of the farm trials in Chipata and Mambwe, did not give what was expected of the experiment. There was no significant difference between treatments when it came to the carbon and nitrogen content. Biochar did not increase the soils content of C as expected, it could not be seen in SOC, HWEC or SOM. Pigeon pea did not have a significant effect on the soils content of N or the plant available N. There was also no effect of biochar on N mineralisation rate. It was surprising that the N mineralisation went down with increasing HWEC (and tot C and tot N) as it was expected to increase. This could potentially be due to an error done under incubation of the soil samples.

There were a lot of significant differences between the two districts. Chipata were found to have lower pH than Mambwe. Both districts experienced increase in pH on the plots where BC were added. Mambwe had higher content of tot C, and thereby higher C/N rate. SOC/clay rate were also found to be higher in Mabwe, ass both clay and SOC content were higher for Mambwe.

None of the hypothesis that this thesis was to answer shown to be correct for the data collected. There is a need for more data.

Sammendrag

Planter trenger tilstrekkelig næring for å vokse. Afrika sør for Sahara opplever en kritisk negativ næringsbalanse, og tilførselen av næring fra gjødsel og mineralisering av organisk materiale er mindre enn næringsutgangen som høstede avlinger, lekkasje og erosjon. Med økende utfordringer i matproduksjonssystemene er det behov for å tilpasse forvaltningspraksis som øker jordens helse og fruktbarhet. Conservational agriculture (CA) er et slikt jordbrukssystem og har som mål å være et bærekraftig, ressursbesparende landbruksproduksjonssystem som intensiverer produksjonen og gir høyere avlinger gjennom tre hovedprinsipper. Dette er minimal jordforstyrrelse (minimum jordbearbeiding), vekstrotasjon og permanent dekning av restmateriale, sammen med integrert ugresskontroll. Tilførsel av biokull blir ofte gjort i tillegg til CA. Dette er slik at jordens karboninnhold mulig kan øke. Rotasjon med pigeon pea er ganske vanlig i Øst-Afrika, mens det er en ny praksis i Zambia. Pigeon pea fikserer nitrogen, og det er håp om å øke både jordens nitrogeninnhold og tilgjengelige plantenæringsstoffer.

Den første dyrkingssesongen av gårds forsøkene i Chipata og Mambwe, ga ikke det som var forventet av eksperimentet. Det var ingen betydelig forskjell mellom behandlingene når det gjaldt karbon- og nitrogeninnholdet. Biokull økte ikke jordens C-innhold som forventet, det kunne ikke sees i SOC, HWEC eller SOM. Pigeon pea hadde ingen betydelig effekt på jordens N-innhold eller tilgjengelige plantenæringsstoffer. Det var heller ingen effekt av biokull på N-mineraliseringshastigheten. Det var overraskende at N-mineraliseringen gikk ned med økende HWEC (og tot C og tot N), da det var forventet å øke. Dette kan mulig skyldes en feil gjort under inkubasjon av jordprøvene. Det var mange signifikante forskjeller mellom de to distriktene. Chipata ble funnet å ha lavere pH enn Mambwe. Begge distriktene opplevde økt pH på de parsellene der BC ble lagt til. Mambwe hadde høyere innhold av tot C, og dermed høyere C/N-forhold. SOC/leirrate ble også funnet å være høyere i Mabwe, siden både leire og SOC-innhold var høyere for Mambwe. Ingen av hypotesene som denne avhandlingen skulle svare på viste seg å være riktig for de innsamlede dataene. Det er behov for mer data.

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1| Introduction

The world's food systems are experiencing massive challenges, such as the effects of the climate crisis, conflict, resource scarcity, inequality, food insecurity, malnutrition, and environmental degradation (Dury et al., 2019). These challenges are essential to tackle as the world's population grows rapidly. This is particularly true for sub-Saharan Africa (SSA), an area highly at risk of climate change, with a relatively dry climate and soils largely depleted in nutrients (Rumley and Ong, 2007). Stewart et al. (2020) reported that nutrient limitation is a central issue contributing to poor yields in SSA. This may further expand agricultural fields, thus enhancing soil degradation (Tully et al., 2015). Most of the SSA population's livelihood is deeply dependent on agriculture (Serdenczny et al., 2016).

Zambia, a country in SSA, with a population of around 21 million people and rapidly expanding, has serious challenges concerning poverty and food resources (World Population Review, 2024). A greater part of the population resides in rural communities, and agriculture is the primary source of income for its rural economy (Ngoma et al., 2017). Smallholder farmers account for more than 80% of the nation's output, and the majority (83%) have small-scale maise production, primarily for their own consumption (Mulenga et al., 2017). With the looming threat of climate change, particularly increasingly erratic rainfall and rapid population growth, the economy and food security of the rural population are likely to come under stress (Ngoma et al., 2017). Thus, the issue of soil fertility and soil degradation need to be addressed to avoid poor productivity (Mapiki and Phiri, 1995). Developing novel technology for sustainable agriculture production is essential to tackle these challenges.

The conditions for agriculture vary across Zambia, and the country has been divided into three agroecological zones (figure 1) based on annual rainfall for the region. Region I cover the valleys in the southern part of the country and receives less than 800 mm of annual rainfall. Region II covers the central parts of the country, receives an average of 800-1000 mm rainfall annually and is the area with the most fertile soils. Region III covers the northern parts and receives above 1000 mm of annual rainfall. The soil in Region III is also highly leached and acidic, which results in low-productivity farmland (Chikowo, 2023).

Plants need sufficient nutrients to grow. Especially micronutrients like phosphorus (P), nitrogen (N) and potassium are essential for growth (Taiz et al., 2015). SSA is experiencing a critically negative nutrient balance, and nutrient input from fertiliser and mineralisation of organic matter (OM) is smaller than nutrient output as harvested crops, leaching and erosion (Farge and Magid, 2004). In addition, as mineral fertiliser has generally been too expensive for smallholder farmers (Magnon et al., 2019), management practices need to be adapted where nutrients are added to the soil through other methods (e.g. manure, N fixing plants).

Nitrogen is an integral component of many essential plant compounds. The plant roots take nitrogen from the soil as dissolved nitrate (NO3-) and ammonium (NH3+) ions. Most of the N in terrestrial systems is found in soil. Understanding N is fundamental to solving many environmental, agricultural, and natural resource-related problems. Deficiencies or excess of nitrogen have significant impacts on the health and productivity of the world's ecosystem (Weil and Brady, 2017, p. 601-605). Across the SSA, there is a need to optimise N use for both nutrient security and to minimise environmental risk (e.g., nitrate leaching and N2O emission). Masso et al. (2017) commented on the challenges of managing N use in SSA and linked it to both insufficient use and excessive loss. About 80% of the countries in SSA have N deficiencies, which leads to chronic food insecurities and malnutrition. Masso et al. further claim that limited research has been conducted to improve N use for food production, and thereby, adoption remains low. This is particularly true for resource-poor smallholder farmers.

Another study by Abera et al. (2012) investigated the effect of C and N mineralisation of organic residues in tropical soil. The residues used were from haricot bean and pigeon pea, both legumes. Legumes are a viable source of N and could offset N depletion caused by continued monocropping of, e.g. cereals (Beyene et al., 2004). They are also found to help sustain soil organic matter (SOM) content, enhance biodiversity, improve physical properties, increase nutrient availability, improve water infiltration, decrease evaporation, and increase the water-holding capacity of soils (Kumar and Goh, 2000; Paalm et al., 2001). Pigeon pea has also been identified as a mobiliser of plant-available P (Ae et al., 1990). Abere et al. found that there are significantly greater NH4+ -N and NO3--N concentrations in the soil when treated with the pigeon peas residues, showing that legume residues can be a potential fertiliser for soil that is depleted in N in tropical soils. They also found that applying legume residues to an immobilised inorganic N pool could be a good strategy to mitigate NO3 loss when the C/N ratio was high. This can reduce environmental pollution and offer high C sequestration as there is little CO2-C loss. The immobilisation of N could also be a great approach for synchronising the N nutrient release and crop N requirement by adjusting the C/N ratio (by mixing residues with different qualities) and by utilising microbes as an ephemeral nutrient pool during the early crop growth period.

Soil organic matter (SOM) is vital for sustainable food production and combat an irreversible climate crisis. SOM is an incredibly important renewable natural resource that supports many important ecosystem services, such as providing food and fibre, regulating climate and water cycles, regenerating fertility, and supporting the immense biodiversity of soils (Smit et al., 2015). SOM is primarily found in forms of particulate organic matter (POM) and mineral-associated organic matter (MAOM), and a small portion (1-2%) is found as dissolved organic matter (DOM). The forms of SOM are defined based on their physical properties, with MAOM being heavier and/or finer than POM and DOM being water-soluble/extractable (Lavallee et al., 2020). The depletion of OM causes a loss in water holding capacity, poor aggregation, acceleration in soil erosion, poor retention of applied nutrients, and reduced soil biological enzyme activities. Combinations of these factors cause a loss in productivity. Loss of SOM may also cause poor ground and surface water quality. Therefore, maintaining and improving SOM in agricultural soils is pivotal to land sustainability (Doran and Parkins, 1994; Gregorich et al., 1994; Campbell et al., 1999).

The conversion of land for agricultural use over millennia, but especially in the past 200 years, humans have consumed large amounts of SOM by accelerating its rate of mineralisation and erosion, resulting in an estimated global loss of 133 Pg C from the top 2 m of soil (Sanderman et al., 2017). Soil represents a significant carbon stock and consists of soil organic carbon (SOC) that is derived from photosynthesis and soil inorganic carbon as carbonated minerals (Wang et al., 2012). SOC is the main component of SOM, and it's estimated that there is around 58% C in SOM (Pribyl, 2010). The loss of SOC is one of the main factors of soil degradation alongside erosion and nutrient loss (Srinivasaraeo et al., 2015). The loss of SOM and, therefore, the loss of C present the opportunity for regenerating SOM, accruing the lost C back into the soil. Large-scale soil C sequestration efforts are needed, and relevant land management practices based on local soil capacities must be adapted (Amelung et al., 2020). Lal (2004) found that a considerable amount of SOC pool can be restored by adopting restorative land use combined with recommended management usage, such as conservation tillage with cover crops and crop residual mulch.

The labile part of SOC is the most readily available fraction for microorganisms and is responsible for improved nutrient availability due to its easy decomposition. The labile fraction comprises 2-5% of SOC (Weigel et al., 2011) The quick decomposition of labile SOC is also associated with the N mineralisation of this fraction. Natural vegetation has higher SOM than agricultural land, and much of the organic litter returns to the soil (Martinsen et al., 2017). To maintain a large SOC stock, it is therefore essential in agricultural systems to use residues from the crop to add nutrients back to the soil.

The passive, complex and stable SOC pool is essential for C sequestration, the soil's water-holding capacity, soil aggregation, aggregate stability, soil structure, and erodibility (Weigel et al., 2011). It is also largely bound to clay particles. Therefore, SOC values are highly site-dependent and strongly correlate with clay content (Weigel et al., 2011). SOC/clay ratio has been proposed as an indicator of healthy soils, as SOC influences a range of soil properties, making it a central indicator of soil function and health. Dexter et al. (2008) determined that a SOC/clay ratio of 1/10 is an approximate limit for SOC with clay particles. This is based on Polish and French soil datasets and tested on Danish soil. SOC/clay ratios of 1/8, 1/10 and 1/13 indicate thresholds of structural condition and are better with higher SOC/clay ratios (Johannes et al., 2017). European Soil Monitoring Law classifies SOC/clay ratio below 1/13 as unhealthy soils.

Soil microbial biomass has been shown to be sensitive to short-term changes in soil management. However, as determining soil microbial biomass is time-consuming and, in most cases, must be measured at field moist conditions or pre-incubation at a certain moisture and temperature, this creates a delay in analysing the changes to SOM content (Ghani et al., 2003). Past studies have successfully used direct extraction methods for determining the labile pool of SOC (Burford and Bremner, 1975; Haynes and Francis, 1993; Fisher, 1993). Sparling et al. (1998) found that hot water extractable C (HWEC) relates well with microbial biomass. Moreover, Fisher (1993) showed that HWEC content in soils was strongly correlated with CO2 evolution, which indicates that a portion of HWEC must be readily available for microbes. The hot water extractable method can also be used to determine a readily available pool of organic N (Keeney and Bremner, 1996). Ghani et al. (2003) used pre-established trial sites on allophonic soils to investigate the impact of long to medium-term pastoral management practices (i.e. fertilisation and grazing intensity) on a range of soil biological properties (e.g. HWEC, water-soluble C, hot-water extractable total carbohydrates, microbial biomass-C and N and mineralisable N). HWEC was found to be the most sensitive and consistent indicator examined at 52 different sites. The impact of different land uses on the amounts of HWEC in the same soil type was greater than what was observed for SOC.

Changes in the weather pattern across the SSA (Stern and Copper, 2011) have made farmers more and more aware of the climate changes, and thereby, there is a potential for greater motivation to adapt to more sustainable and climate-smart agricultural practices among farmers (Mubaya et al., 2012). Changing to a more climate-smart agricultural solution is crucial in tackling the agricultural challenges of a changing climate. Moreover, with the challenges of rising population, there is a need to increase agricultural productivity and incomes sustainably. Agriculture needs to adopt farming systems that are resilient against the impact of climate change and contribute to climate change mitigation where possible (FAO, 2017).

Conservational agriculture (CA) is one such farming system that uses novel technology and aims to be a sustainable, resource-saving agricultural production system that intensifies production and produces higher yields through three main principles. These are minimal soil disturbance (minimum tillage), crop rotation, and permanent residue cover, together with integrated weed management (Farooq and Siddique, 2015).

However, the effect of CA is debatable. A meta-analysis done by Corbeels et al. (2020) of 933 studies across 16 SSA countries reports that CA only causes a 3-4% increase in yield compared to conventional practices of seven major crops. Their report concluded that CA may bring soil conservation benefits, but it is not a technology for smallholder farmers to overcome low crop productivity and food insecurity. Thierfielder et al. (2017) investigated how climate-smart CA is. Based on analyses of research done in Southern Africa, CA has the potential to adapt to some negative effects of change in climate, like dry spells, and it is widely accepted that it increases infiltration, soil water retention, and reduces evaporation.

Other studies have shown the potential of CA in increasing crop yield, through improving physical, chemical, and biological soil properties (Muchabi et al., 2014). Umar et al. (2011) also showed that the annual addition of crop residues improved the SOM. However, this is only sometimes the case, according to a meta-analysis conducted by Powlson et al. (2016). They found that SOC stocks under CA in SSA increased between 0.28 and 0.96 Mg C/ha/yr. Yet, there were greater variations in values, and a significant portion of the cases had no noticeable increase. In addition, a great number of reported SOC stock increased under CA are incorrect due to an overestimation based on inappropriate soil sampling methodology: equal soil depth rather than equal soil mass. It is essential to understand if the significant increase in SOC stock comes from a net additional transfer of C from the atmosphere to land (genuine climate change mitigation) or if it is a spatial redistribution of organic C in soil. Powlson et al. concluded that the SOC increase caused by crop diversification was almost certainly a genuine mitigation. Powlson et al. also commented that CA adoption by smallholders in these areas faces social and economic barriers and that it would be unwise to assume CA to be a large-scale strategy for climate change mitigation.

In addition to CA adaption, the application of biochar (BC) as a soil amendment has been proposed to enhance soil quality and improve crop productivity in weathered and eroded soils (Biederman and Harpole, 2013). The International Biochar Initiative defines biochar as an alkaline carbonaceous solid material derived from the thermochemical conversion of organic feedstock in an environment limited in oxygen, called pyrolysis (Ghodszad et al., 2021). Biochar amendments have been shown to result in more developed root systems and higher yields (Abiven et al., 2015). A study by Yadav et al. (2018) found that amendment of soils that have potentially higher losses of nutrients through leaching had an increase in fertiliser use efficiency with the use of biochar.

A meta-study by Singh et al. (2022) investigated the influence of biochar application on different soil properties and crop productivity. The study distinguished between different experimental setups, laboratory greenhouse and field experiments; in total, 59 studies that were published between 2012 and 2021 were analysed. In general, the effect of biochar application on most of the soil properties was greater for the experiments in the laboratory and greenhouse than for the field experiments. Biochar may undergo weathering and degradation (Anderson et al., 2014), while it also may be diluted due to mixing into soil profile due to tillage (Schatter et al., 2018). Both factors will lead to a decrease in the effect of biochar on soil properties (Li et al., 2020). The protected conditions in greenhouse or laboratory studies combined with litter or no dispersion provide less change in biochar concentrations and properties, thereby having a greater effect on soil quality.

Studies have also shown that the biochar feedstock and pyrolysis temperature influence the biochar's properties. Li et al. (2019) review earlier reported data from independent studies to see if biochar's properties could be predicted. As different feedstock is used to produce BC under different pyrolysis conditions, the resulting BC would differ in physicochemical properties, impacting biochar's agricultural and environmental performance in its real-world applications. Even though other factors might impact BC properties, it was found that many critical properties, such as biochar yield, pH, CEC, specific surface area, ash content, volatile matter content, and elemental composition, have been found to correlate significantly with pyrolysis temperature.

It is common to use agricultural waste material to produce biochar. Cornelissen et al. (2013) observed that using biochar in combination with CA practice motivated farmers to generate their own material. The use of agricultural waste material as sole biochar feedstock is recommended to avoid putting extra pressure on other limited resources (e.g. wood) (Cornelissen et al., 2013). As maise is one of the major crops in Zambia, it is also the main agricultural waste material. A study done by Shareef et al. (2018) found that increasing the pyrolysis temperature from 300°C to 600°C led to an increase in carbon content for biochar made from maise straw and corn cob. The increase was 67.5 to 76.93% in maise straw biochar and 71.6 to 80.4% in corn cob biochar. They also found that biochar made from maise straw increases pH more than corn cob. The higher increase was for biochar made at a pyrolyse temperature of 600°C. The increase in pH was for maise straw BC 0.21 and 0.53, for 300°C and 600°C, respectively. For corn cob BC, the pH increased by 0.18 to 0.33 for 300°C and 600°C, respectively. Another study done by Adekanye et al. (2022) also looked at maise cob BC and found, however, that biochar yield decreased with an increased temperature. Moreover, BC produced at 300°C had the highest fixed carbon (60.5%).

One feedstock for BC is the woody biomass of pigeon pea (PP). The crop has gained more interest and has been suggested for rotation with other crops, such as maise, under CA. Maise is a major staple food in SSA, but low soil fertility, limited resources and drought keep yields low. Therefore, cultivation of maise intercropped with PP is common in some areas of eastern and southern Africa (Myaka et al., 2006). Perennial PP may have a greater capacity to replenish soil fertility than annual grain legumes, as they can exploit the residual water and subsoil nutrients that crops cannot utilise, withstand drought, and hence produce higher biomass. They also grow year-round and thereby may lead to higher N fixation (Giller et al., 1997). It is not only of fertiliser value, but it also provides valuable dry-season animal feed and seeds for human consumption (Abebe and Diriba, 2002). Other advantages of PP include no recurring establishment costs, the opportunity to grow crops simultaneously without sacrificing land, improved soil physical conditions, and higher water infiltration because of their root activity (Rao et al., 1998). It also offers the benefits of improving long—term soil quality and fertility when used as green manure, cover crop (Bodner, 2007), or alley crop (Mapa and Gunasena, 1995). Sogbedji (2006) found that maise yields increased by 32.1% in West Africa by using PP as a cover crop. This is probably because PP contributes about 40 kg N/ha through N fixation, leaf litter fall and roots (Rao and Willey, 1981). PP is also known for its ability to access insoluble P in soils that are low in P and increase the availability of soluble P from following cash crops in the rotation (Hector and Smith, 2007).

A study done by Myaka et al. (2006) compared maise-pp intercrops to sole maise grown using farmers' practices. Intercropping maise and PP increased the total system yield compared to sole maise when looking at biomass, N and P accumulation. The PP planted in maise was not found to reduce the accumulation of dry matter, N, nor P in the maise grain. There were also no differences in harvest indices of maise, a total soil C and N content and inorganic N content, and nitrate and ammonium were not affected by two seasons of intercropping when compared to sole maise. PP was found to increase the recirculation of dry matter, N and P, which can have a long-term effect on soil fertility. Dakora and Keya (1997) evaluated traditional cropping systems in SSA. They found that crop rotation involving legume and cereal monoculture is more sustainable than intercropping, a more dominant cultural practice. Abebe et al. (2016) showed that pigeon peas had several agronomic and environmental benefits when rehabilitating degraded land, high capacity in fixating N and improving the soil's physical condition. PP have deep taproots, which take nutrients and water from deeper soil horizons. It is also known for its ability to access insoluble phosphates in soils with low P and increase the availability of soluble P from following crops in the rotation (Abebe et al., 2016). Due to its high biomass production, with several harvests on one plant, there is also a potential for additional income for smallholder farmers. But despite its popularity in eastern Africa (e.g. Kenya and Uganda), pigeon pea is used little in Zambia.

1.2| The project

This study is a part of the research project NORDPART-2016/10498 (Academic cooperation on sustainable, climate-smart agriculture between Zambia and Norway) at MINA, funded by HK-DIR (Norwegian Directorate for International Collaboration in Higher Education). The aim of the project is to study the effect of maize – pigeon pea rotation under CA with biochar, under field conditions. And where leftover biomass after harvest can be used as feedstock for biochar production and applied as soil amendment. And to see the comparison between two agroecological regions (I and II).

1.3| Research objectives and hypothesis

The aim of this thesis is to assess the effect of planting pigeon pea and the addition of biochar, on soils content of carbon and nitrogen in two different agroecological regions in Zambia (agroecological region I and II), under conservational agriculture.

The research question asked are: What is the effect of planting pigeon pea and adding biochar to the soil on the soils content of carbon and nitrogen? For carbon, what effect does it have on soil organic carbon content and hot water extractable carbon? And for nitrogen, what effect does it have on tot N and mineral N, and what is the effect on N mineralisation rate?

The following hypothesis were tested to address this:

1. Adding biochar will increase SOC and HWEC.
2. Planting pigeon pea will increase nitrogen content and availability.
3. Adding biochar will increase N mineralisation rate.

2| Material and methods

Field work was done in collaboration with another NMBU master student Jostein Reitan Fyrvik. There will therefore be some similarities in the description of study area, experimental setup, and soil sampling.

Lab work was done at NMBU, where as background data and some additional data were done at UNZA by Miyanda Moombe and Gideon Musukwa (unpublished data) and is found in appx. B.

2.1| Study area

2.1.1| The sites

The field work and soil sampling were done in the Eastern Province of Zambia in the districts of Chipata and Mambwe, the red arrow in figure 1 shows where Mambwe and Chipata is. Mambwe is the top arow, and Chipata is the bottom arrow.

Figure 1 illustrate the different agroecological regions in Zambia. Zambia has a rainy season from around November to May, and the remaining months are dry (Arslan et al., 2014). From June through November, Zambia experience a long dry season. And there is only on cropping season per year. Sowing starting around November/December and harvesting happening in May/June (FAO, 2022).

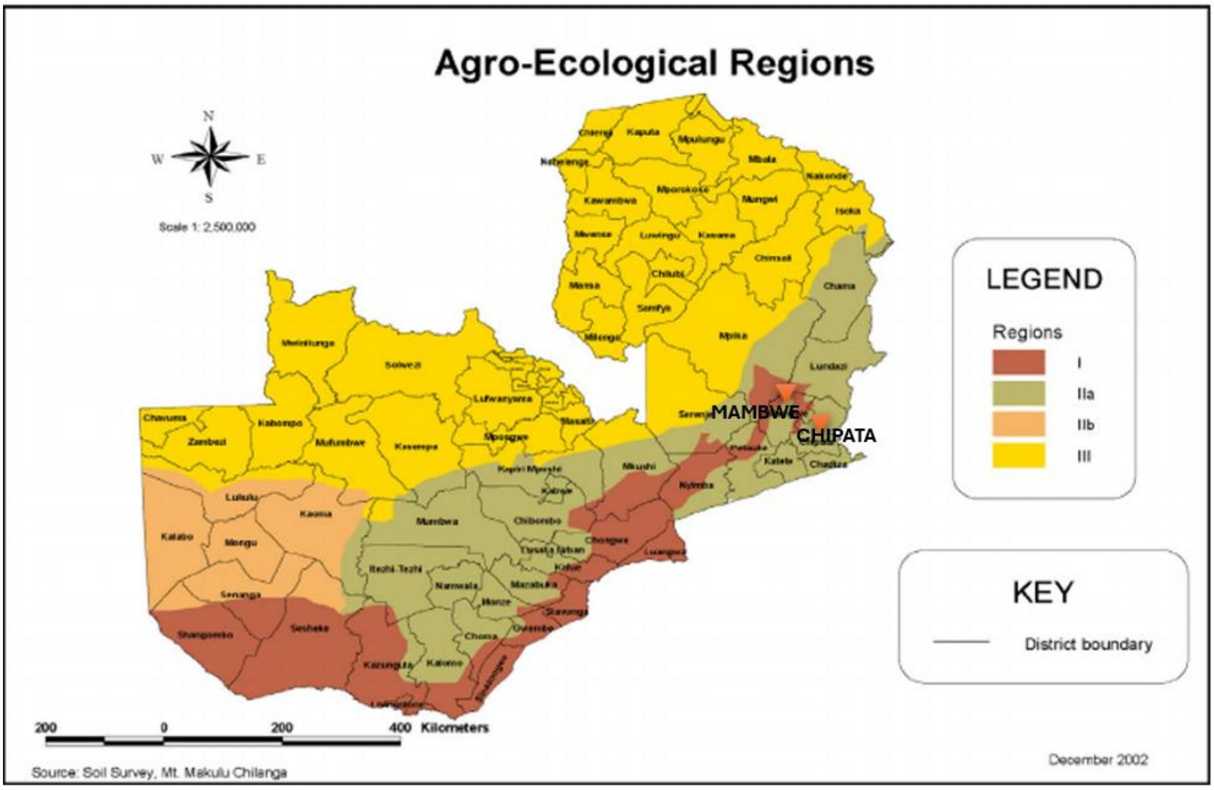

Figure 1: Zambia's administrative boundaries, with its agroecological regions I, IIb, IIa, III. Amount of precipitation determine the agroecological regions; I) less than 700mm, IIa/b) 800-1000mm, III) 1000-1500mm. The red arrows show the districts of the farm trials; Mambwe is the top red arrow, and Chipata is the bottom red arrow. Source: FAO (CFA, Zambia Branch Homepage).

In 2022, 18 smallholder farms were selected in Eastern Province. These include ten farms in the Chipata District and eight in the Mambwe District. Initially, there were ten farms in the

Mambwe district, but two farmers withdrew. The thesis did not include two other farms in Mambwe, as they had planted sunflowers on some of the trial plots. Thereby, only six farms in Mambwe are included.

Agroecological region I is represented by the Mambwe district and is a dryer area, with mean annual precipitation being between 600-800mm. Mambwe has a relatively dry tropical savanna climate with warm to hot temperatures and distinct wet and dry seasons. October and November are the hottest months, while June and July are the coolest months. The wet season, from November to March, experiences significant rainfall—the dry season, from May to October, has little precipitation. The soils on the farms in Mambwe are Luvisols. Luvisols are described by FAO (2015) in World Reference Base for Soils Resources 2014 as “Soils with a paedogenetic clay differentiation (especially clay migration) between a topsoil with lower and subsoil with a higher clay content, high-activity clays and a high base saturation at some depth”.

Agroecological region II is represented by Chipata district, a wetter area with mean annual precipitation between 800-1000mm. Chipata has a tropical savanna climate with distinct wet and dry seasons. Where summers are warm and hot, reaching peak temperatures in October/November. Winters are milder, with July being the coolest month. The wet season, from November to March, brings high humidity and significant rainfall. The soils on the farms in Chipata are Acrisols. Acrisols are described by FAO (2015) in World Reference Base for Soils Resources 2014 as “very acid. Strongly weathered acid soils with low base saturation at some depth”.

The farm trial sites were previously under Conservation Agriculture (CA) before they were used for the research. These fields were primarily used to grow maize, but also groundnuts, soybean, and cotton. A complete list of former land use can be found in appendix A, providing a comprehensive understanding of the land's history.

2.1.2| Experimental setup

Each farm was under CA and had four treatments: with and without biochar, where either pigeon pea or maize is planted. In this thesis, the treatments will be maize (M), maize with biochar (MB), pigeon pea (PP), and pigeon pea with biochar (PPB). Figure 2 shows the setup for the 2022/2023 growing season. Maize cob biochar was added to the two biochar-amended plots on each farm at a rate of 4 t/ha (i.e. 500kg per 1250 m2).

Planting was done in December 2022, with biochar added to two plots and fertilizer added to maize plots. The fertilizer rate is 200 kg/ha (Compound D (ratio N-10; P2O5-20; K2O-10; S-6) and 200 kg/ha Urea (N = 43%).

Chipata had mainly rip lines, whereas Mambwe had mainly basins. Rip lines were 20 cm deep, and basins were 20 cm, 20 cm wide and 35 cm wide.

The plots with only M could be considered control/background. Most of the fields before farm trials were established were used to grow maize under CA. Background data from UNZA used some different lab analyses than lab analyses used in this thesis, e.g., for tot N.

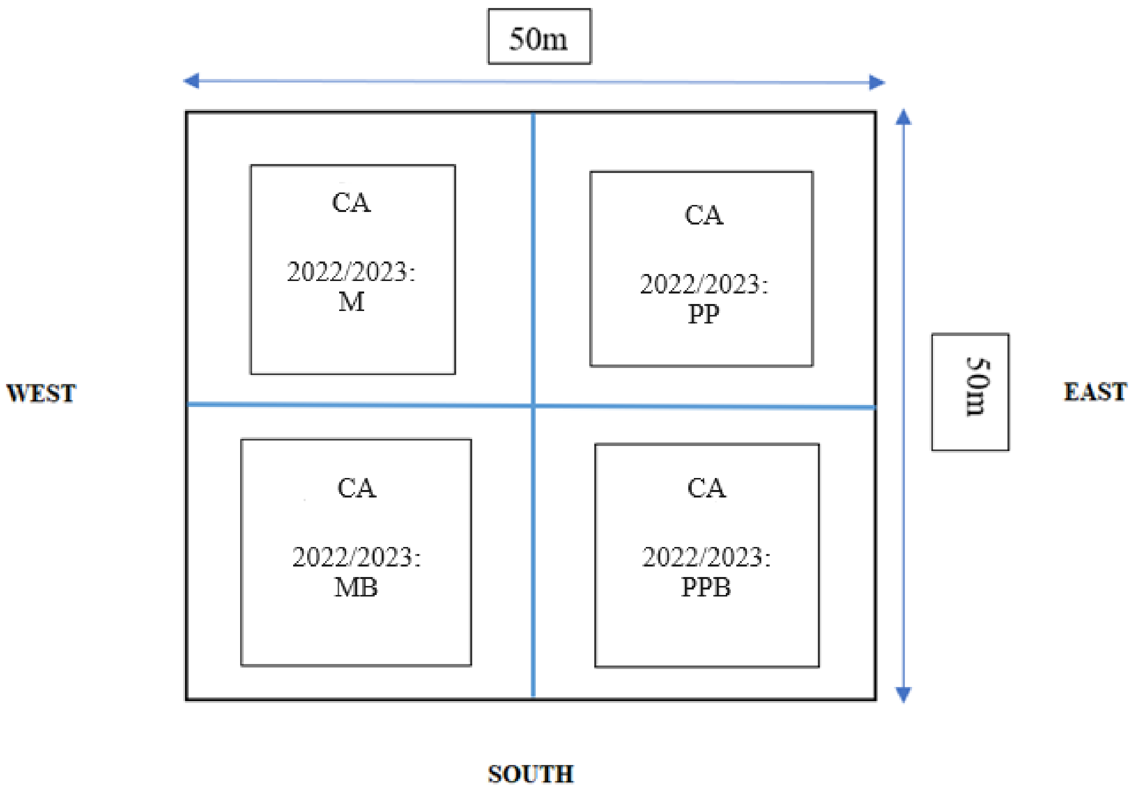

Figure 2: An example of a layout in the farm trials. One each farm a 50m x 50m square was set up in 2022 and divided into four equally sized quadrants (25m x 25m = 625 m^2). Addition of fertilizer to maize plots and biochar, as well as planting was done in December 2022. All four quadrants were under conservational agriculture (CA), using basins/rip line. Two of the quadrants were planted with maize (M) and two with pigeon peas (PP), where one of the maize and one of the pigeon peas were amended with 250kg of maize-cob biochar each (MB and PPB).

2.2| Soil sampling

In August 2023, following the crop harvest, soil samples were collected using the composite sampling method. Altogether, 68 soil samples were collected, and 64 of these soil samples (16 farms) were used in the thesis. 16 samples were taken from each of the treatments: M, MB, PP, and PPB.

We collected a composite sample from each of the four plots from 8 basins/rip lines at a depth of 0-20cm. The spots for the soil sampling in each plot were randomly selected. The samples in the plots with BC were randomly selected but were also selected on the basis that BC was visible in the sample. The upper few mm of soil was scraped away to avoid influence from litter, as there was a varying amount of litter on top of the soil. For pigeon pea plots, it varied if the farmers had removed the litter, and for maize plots, the plant was left after harvest.

The soil samples were collected using a Chaka hoe, a common farming tool in Zambia. It is quite an efficient tole when the soils are dry and hard, as they were when we collected the samples. The 8 sub-samples were mixed well in a bucked, and bigger soil pieces were broken into smaller pieces. After mixing the soil well, it was then sieved in the field using a 2mm mesh sieve. In retrospect, this sieving may have caused the loss of some of the large BC particles as we did not find back the expected BC-induced increase in SOC (figure 6).

We collected about 500g of soil into zip-lock bags. As the samples were already quite dry (dry season), it was decided not to air dry them. At UNZA, the soil was divided between UNZA and NMBU, and 200g of each sample was brought back to Norway.

2.3| Laboratory analysis

2.3.1| Bulk density

Bulk density was measured using scoop method in the lab. It was done on the 40 samples used to measure N mineralization rate. The sample was stirred well in the zip-lock bag with a scoop that had the volume of 10 ml. The scoop where then carefully filed with the soil sample and filled full of soil. The top of the scoop where then scraped off with a flat object (wooden ruler), so that the volume of soil was 10 ml. The scoop where then placed on the weight, which beforehand had been tared for the weight of the scoop, and the soils weight where measured. The weight of the soil was then used in the calculation of the bulk density with regards to the soil texture. The calculation is based on Semb (1985) and modified by Øien (unpublished). The connection between volume weight in lab (V_{LAB}) and volume weight under natural storage (VOL) is dependent what it is most of; sand, silt, or clay (soil texture). BD was calculated for VOL in consideration to sand (VOL_{SAND}). The formula is found in appx. A.

2.3.2| pH

pH_{H2O} was measured in a soil-water suspension with 10 ml soil and 25 ml distilled water in plastic bakers with lids, in accordance with Krogstad and Børresen (2019). They were shaken a few times by hand, before being left overnight to let the soil-water achieve equilibrium. The morning after the samples were shaken again a few times by hand. The pH was measured with the pH meter PHM210, calibrated with pH 7 and pH 4 buffer solutions. When measured it was made sure that the electrode did not touch the soil sediment. In between each measurement, the electrode was rinsed thoroughly with water.

2.3.3| Total C and total N

Total carbon and total nitrogen were analysed using an element analyser described by Nelson, D.W. and Sommer (1996) and Bremmer and Mulvaney (1982) respectively. The sample used for this analysis were crushed with a mortar and dried at 55 °C beforehand to remove the last of the water remaining. Around 200 mg of soil from each of the samples was weighed in on tinfoil and analysed by Leco CHN628. Leco CHN628 limit of detection for both C and N is 0.02 mg.

As an independent analysis of organic C was not included in this thesis total C will be discusses as total organic carbon (TOC). Results of tot C are almost equal to organic C, due to low pH of the soil (Martinsen et al., 2017)

C and N stocks were calculated based on volume of soil by multiplying depth of sampling, BD, and elemental concentration. Mean value of BD for each district were used. Calculation found in appx. A.

2.3.4| Mineral N and N mineralization

The mineralization rate of N was determined in a 60-days incubation at room temperature. The experiment uses the same approach as Munera-Echeverrie et al. (2020). The experiment contained three parallel sets of the same 40 samples, in total 120 samples (40 samples x 3 set). Five farms from each district were selected based on total N content found at the farm (low, middle, and high mean value; appx. C). Set 1, 2 and 3 were removed after 0, 30 and 60 days. No replica within each set. Of each of the air-dried soil 8 g was added to 50 ml polypropylene tubes and the moisture content was adjusted to 36% (v/v). Based on the mean bulk density of Chipata and Mambwe, 2.2 ml and 2.3 ml respectively, distilled water were added to the samples. The lids were placed loosely on the tube, to allow gas exchange. After water was added the 40 tubes for day 0 were immediately capped and placed in the freezer for storage (at -18 ˚C). Every 10-12 day the water was replenished in the incubated samples after weighing. It is important to check the samples regularly to see if they are getting to dry, as water needs to be replenished before the samples dries out. After 30 and 60 days also the samples of the second and third set, respectively, were removed, capped and frozen at -18 ˚C. Shortly after the incubation was finished, the three frozen set of incubated soils were thawed and extracted with 20 ml 2M KCl. The tubes were shaken horizontally for 1 hour at 200 strokes per minute and filtered using Whatman filter (589/3). The KCl extract were analysed with respect to the concentration of mineralised N (NH_4^+ and NO_3^-) by Flow Injection Analysis (FIA tar 5010). The potential N mineralization rate was calculated by subtracting the initial amount of NH_4^+ and NO_3^- at day 0 (in mg/kg soil), from the amount determined after 30 days and 60 days (in mg/kg soil). The concentration of NH_4^+ and NO_3^- (expressed in mg NH4-N/kg and mg NO3-N/kg) at day 0, was assumed to represent the concentration of mineral N at the time of sampling (1st of August to 5th of August). The values may have changed during storage following sampling. Limit of detection for FIA is >0.32 mg/kg.

2.3.5| Loss on ignition (LOI)

Of each soil sample, 5-10 g (roughly a tablespoon) was weighed into a previously weighed crucible and dried in a drying cabinet for a night (at least 6 hours) at 105 ˚C. The crucible with the sample is then cooled down for around 30 minutes after turning off the drying cabinet and weighed after 30 minutes to determine dry matter content. Next, the loss on ignition (LOI) is determined. The crucible with the dried soil was placed in a calcinating oven and calcinated overnight (for at least 3 hours) at 550 ˚C. After the crucible with the samples had cooled down for at least 30 minutes the weight of the crucible with the sample was measured. This was done in accordance with Krogstad and Børresen (2019). The calculation of dry matter content and loss on ignition is found in appx. A. LOI were also correlated for clay content (Krogstad and Børresen (2019) and is found in appx. A.

2.3.6| Soil organic carbon (SOC) calculation

SOM is assumed to contain 58% C (Pribyl, 2010). This percentage is widely used, and sometimes credited to research van Bemmelen (Pribyl, 2010). Organic carbon content could thus be estimated as a mass percentage of bulk soil by multiplying LOI (correlated) by 0.58, resulting in $SOC_{(LOI)}$.

2.3.7| Hot water extractable carbon (HWEC)

The method of HWEC is based on Ghani et al. (2003). HWEC is an estimate of the amount of labile C (the fraction of easily degraded organic matter). HWEC was determined according to Dong et al. (2020). 4.5 grams of soil were weighed into 50 ml centrifuge tubes, to which 45 ml of deionized water was added. The samples where then put into a hot water bath at 80 ˚C for 17 hours. The tubes where so centrifuged for 10 minutes with 3803 RCF (Relative Centrifugal Forces) and filtered through 0.45 µm cellulose nitrate membrane filters. The filtrates were put in a fridge to keep cold until they were analysed for dissolved organic carbon (DOC) by combustion catalytic oxidation method using the Total Organic Carbon Analyzer TOC-V CPN.

2.4| Statistical analyses

All statistical analyses were conducted using R software, version 4.3.3 (2024). Linear mixed effect models (R extension package lme4 (Bastes et al., 2015)) were used to test all data against the effect of district and treatment. Differences between variables were analysed by Tukey test at 0.05 significance. Linear regression was used to find correlation for some variables. Pearson correlation at 0.05 significance and 95% confidence were used for liner regression. Plotting was done using ggplot (Wickham, 2014) and Microsoft Excel version 2404.

3| Results and discussion

Appendix C presents all data that were collected. Unpublished data done at UNZA by Miyanda Moombe and Gideon Musukwa is found in appendix B.

The data is shared with NMBU master student Jostein Reitan Fyrvik. Some of the data used will therefore be similar (such as pH, texture, and bulk density).

3.1| pH, texture, and bulk density

There is a significant difference in pH between districts ($p = <2e-16$) (figure 3), with Chipata having a more acidic soil compared to Mambwe. The addition of BC is expected to increase the soil pH, this is supported by earlier studies that indicated BC’s liming effect on acidic soils (Glaser et al., 2001; Chan et al., 2007; Novak et al., 2009). Figure xx shows a significant effect of treatments ($p = 0.0401$). The plots that have BC has higher pH (Figure 3). Less of a difference between PP and plots with BC (MB and PPB).

The pH adjustment is crucial as it influences nutrient availability for uptake in plants. Specifically, a pH range of 0.6-0.5 is deemed optimal for enhanced macronutrient availability, while macronutrients become less available at higher, alkaline pH levels (pH > 7.0) (Ferrarezi et al., 2022). All the farms in Chipata have soils with a pH under 6.0, thereby adding BC to the soil could be a great way to increase the pH and ensuring that the nutrients is plant available.

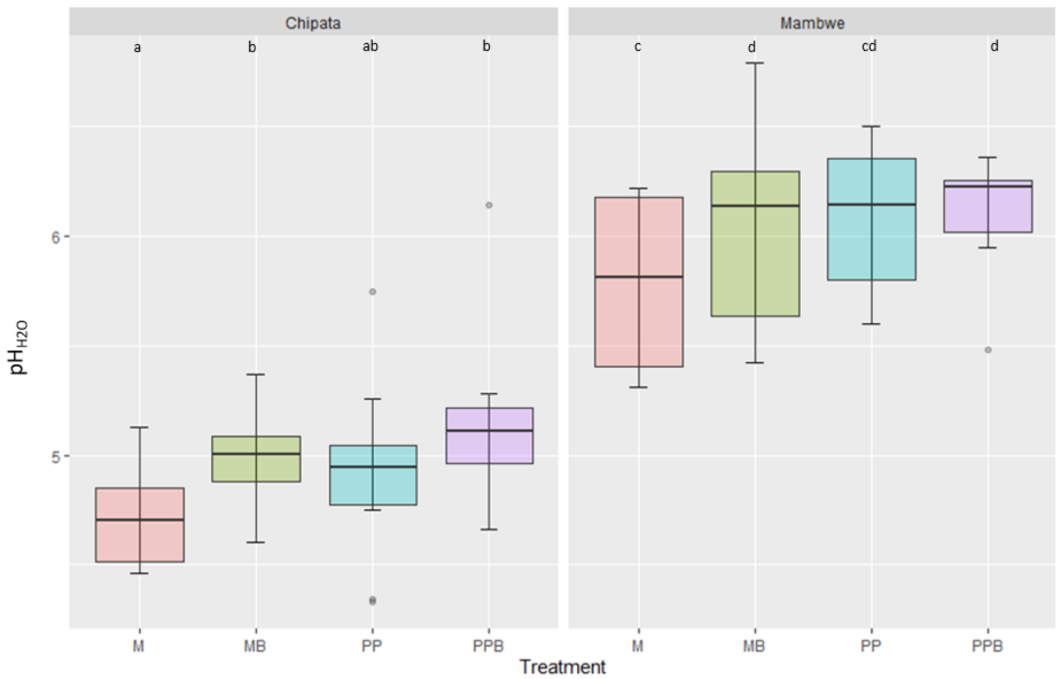

Figure 3: pH for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. Significant difference between districts (p<0.05). pH was higher in treatments with BC, especially compared to treatment M (p<0.05).

Most of the soils were found to be sandy clay loam (figure 4). This was the case for both Chipata and Mambwe.

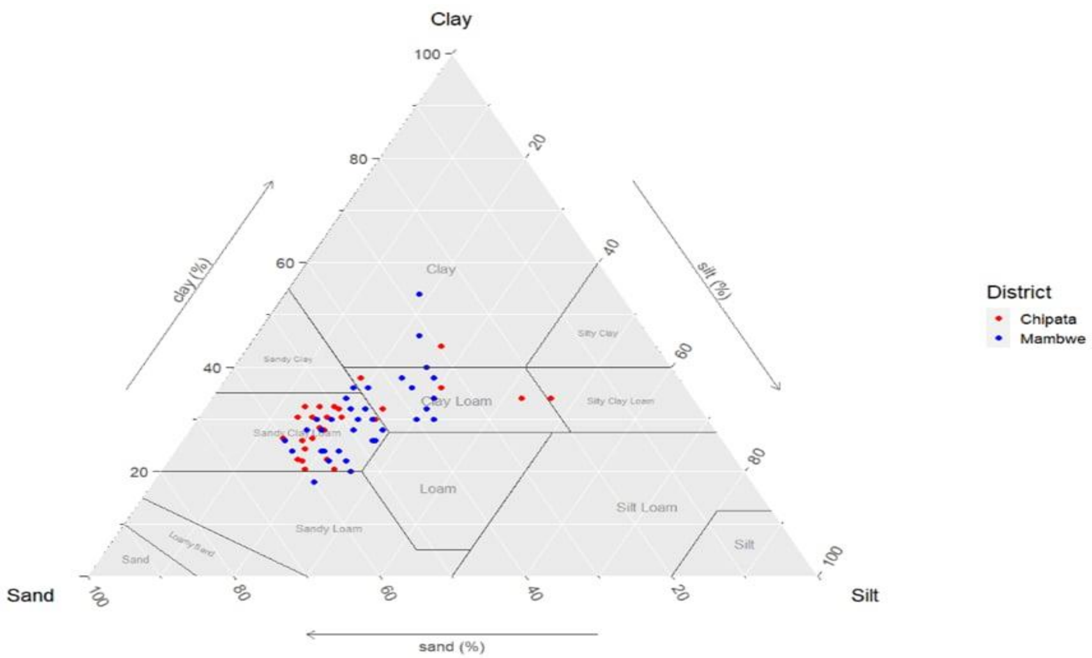

Figure 4: Soil texture triangle (USDA) for both districts. Chipata as the red points and Mambwe as the blue point. Mainly sandy clay loam for both districts.

The mean bulk density in Chipata were found to 1.34 g/cm^3, and for Mambwe it is 1.27 g/cm^3. Although there's no significant difference observed in bulk density between districts or in treatments (figure 5), BD is expected to decrease with the addition of BC. BC is lower in density compared to common agricultural soils (Khademalrasoul et al., 2014). This were found to be true in a study by Verheijen et al. (2019). It is possible that by living in the field and potentially losing some of the BC, the expected difference between plots with BC and plots without BC is lost. This is also evident in the lack of significant increase in SOC content (figure 6; table 2).

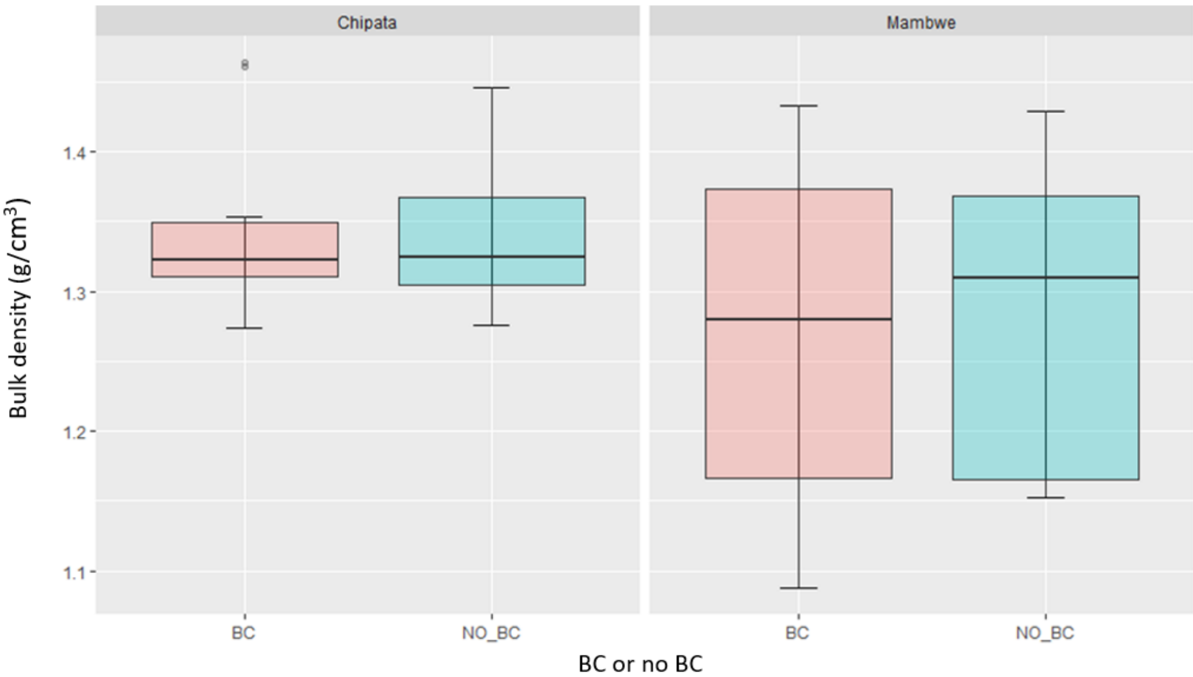

Figure 5: Bulk density for both district and in the plots with BC and without BC. Mean bulk density for Chipata is 1.34 g/cm^3 and for Mambwe it is 1.27 g/cm^3.

3.2| Carbon and nitrogen

Table 1: Average of different soil properties ± standard error (SE) for the different treatment in each of the districts, Chipata and Mambwe.

DISTRICT	**TREATMENT**	**TOT C% MEAN**	SE	**TOT N% MEAN**	SE	**C/N MEAN**	SE	**SOC/CLAY** MEAN	SE
CHIPATA	M	1.36	±0.18	0.08	±0.01	17.5	±0.88	12.1	±1.76
	MB	1.60	±1.16	0.08	±0.01	21.6	±1.71	11.4	±2.04
	PP	1.41	±0.19	0.09	±0.01	18.2	±0.49	13.4	±2.13

	PPB	1.63	±0.18	0.09	±0.02	20.9	±2.07	11.3	±1.40
MAMBWE	M	1.83	±0.26	0.11	±0.02	18.1	±1.08	18.8	±5.91
	MB	2.24	±0.53	0.11	±0.03	20.9	±1.14	22.3	±7.35
	PP	1.92	±0.21	0.11	±0.01	18.2	±0.46	14.8	±4.33
	PPB	1.74	±0.32	0.09	±0.02	19.1	±1.63	21.4	±5.20

Despite expectations, there's no significant difference between treatments for tot C (~SOC) content (figure 6). The addition of BC is expected to increase SOC due to residue retention content with and should improve the build-up of SOM. Similarly, there's no significant difference in soil organic matter (SOM) content between plots with and without BC (appx. D).

This could be due to sieving in field, and thereby potentially having lost some of the bigger BC particles. But there was also often time observed lite BC in the disturbed soil. Which could indicate that BC was not fully mixed inside the basins.

There is however a significant difference between districts and tot C content ($p = 0.0158$), where higher tot C content is found in Mambwe.

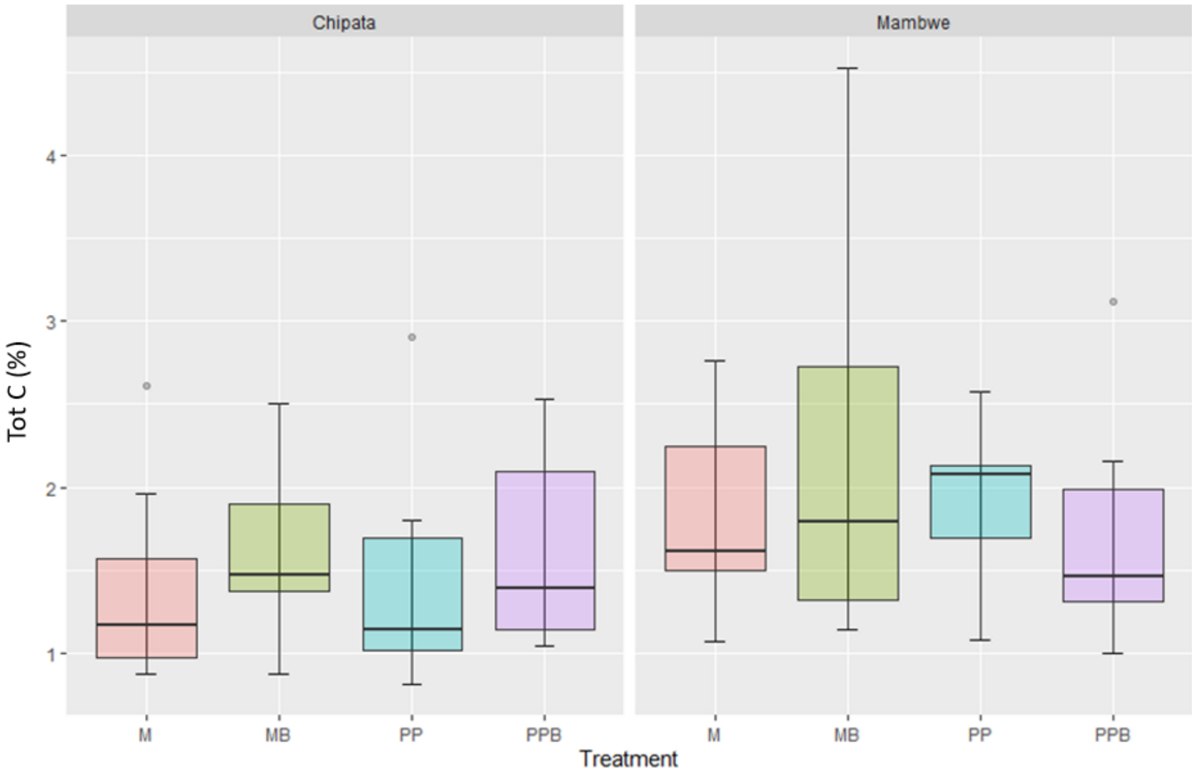

Figure 6: Tot C (SOC) for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. No significant differences (p>0.05).

Difference in total N content did not vary significantly between treatments and districts (figure 7). As pigeon pea is a nitrogen fixating plant there is an expectation of finding higher total N in the plots with pigeon pea. However, there doesn't seem to be any significant difference between total N found in plots with pigeon pea and total N found in plots with maize. It is possible that the total pool of N is much greater than the new input derived from the atmosphere by N fixation.

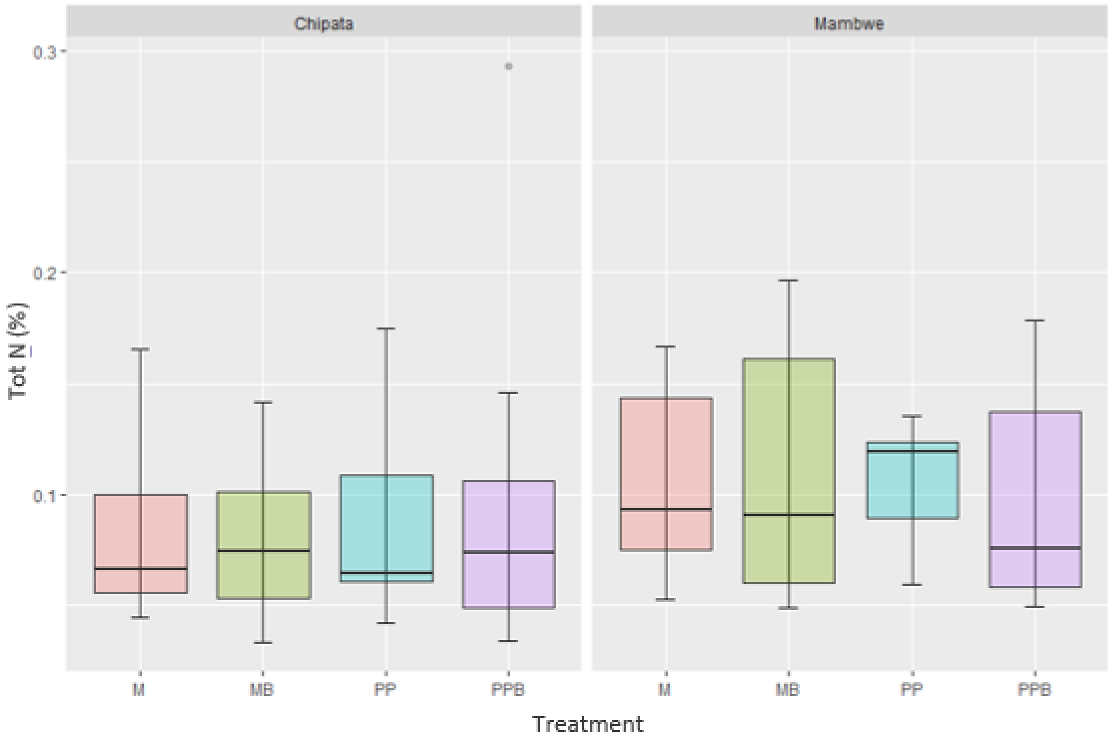

Figure 7: Tot N for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. No significant difference between (p>0.05).

There are no significant differences between districts and between treatments on plant available N (figure 8). There is an expectation of increase in plant available N in plots with PP. There is a difference between NO_3^- - N and NH_4^+ - N from soil KCl extraction. Higher NH_4^+ content is found, which is interesting as when looking at N mineralisation rate, there were a loss of NH_3^+ (figure 13). This indicate that there is a nitrification process over the 60 days of incubation, and NH_4^+-N is converted to NO_3^- - N. Figure 8 gives an indication for what the NO_3^- and NH_4^+ content was at sampling.

Note KCl extraction was not done in the field, and some NH_4^+ content was found in the blanks likely due to contamination in the KCl solution. However, the total concentration of NH_4^+ - N was very low.

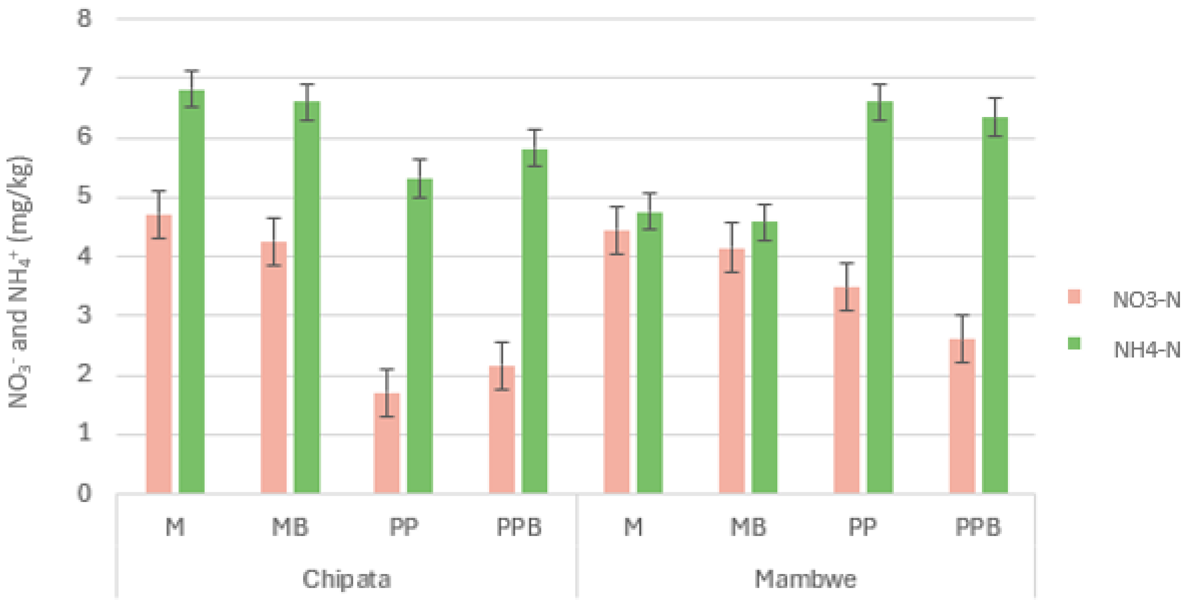

Figure 8: Mean amount of KCl extractable NO_3^- and NH_4^+ in the soil for each treatment in both districts. Potential NO_3^- and NH_4^+ content at sampling. Error bars show standard deviation.

Cornelissen et al. (2011) reported higher nitrification rate in Zambia soil with BC, this is however not visible here (figure 8). Zaman and Nquyen (2010) found that the lime effect by BC addition can result in increase in NO_3^- concentration in soil. This is also not confirmed here, as there is no significant difference between the treatments.

N content found in topsoil (A horizion) normally range from 0.02-0.5% N by weight and in cultivated soils it's expected to find about 0.15% N (Weil and Brady, 2017, p. 604). Tot N were found to be above 0.02 in all plots, but in a lot of the plots the tot N% were found to be under 0.15%. This is clear from the mean tot N% per district and treatment found in table 1. Most soil nitrogen is present as a part of organic molecules, therefore, the distribution of soil nitrogen closely parallels that of SOM, which typically contains about 5% nitrogen. Except where large number of chemical fertilizers have been applied, inorganic nitrogen seldom accounts for more than 1-2% of the tot N in the soil (Weil & Brady, 2017, p. 604). Figure 9 shows that tot N and tot C closely relates (tot C and SOM is highly correlated, appx D).

The hypothesis that pigeon pea will increase soil N content and plant available N content is rejected.

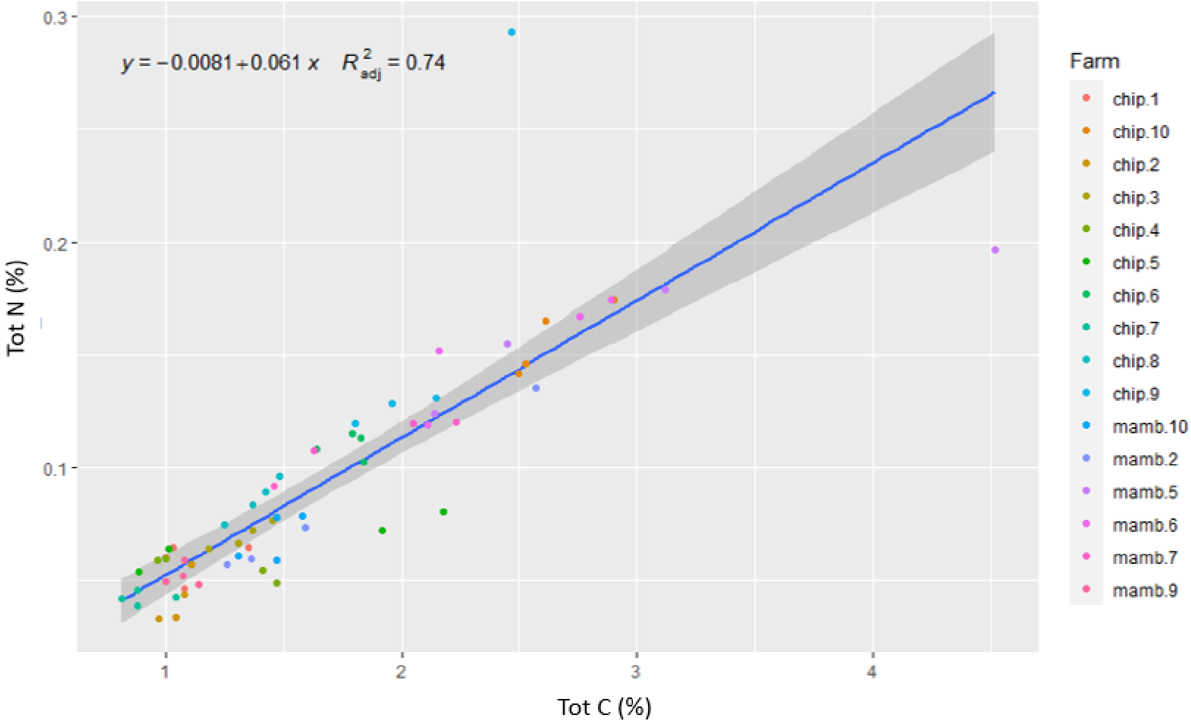

Figure 9: Relationship between tot N and tot C rate for the 10 farms in Chipata and for the 6 farms in Mambw

C/N were found to be higher in plots with BC (figure 10), especially for treatment MB and M. The C/N data is however highly sensitive as tot N is low, especially for Chipata (figure 7; appx. C). The C/N ratio is important as microorganism need a good balance of carbon and nitrogen (25-35) to remain active (Debbarma and Choudhary, 2023). The C/N data is low, which could indicate a high decomposition rate of SOM by microorganism. As the C/N ratio is higher in plots with BC (MB), SOM content would be expected to be higher. But as mentioned above there is no significant increase in SOM in plots with BC (appx. D)

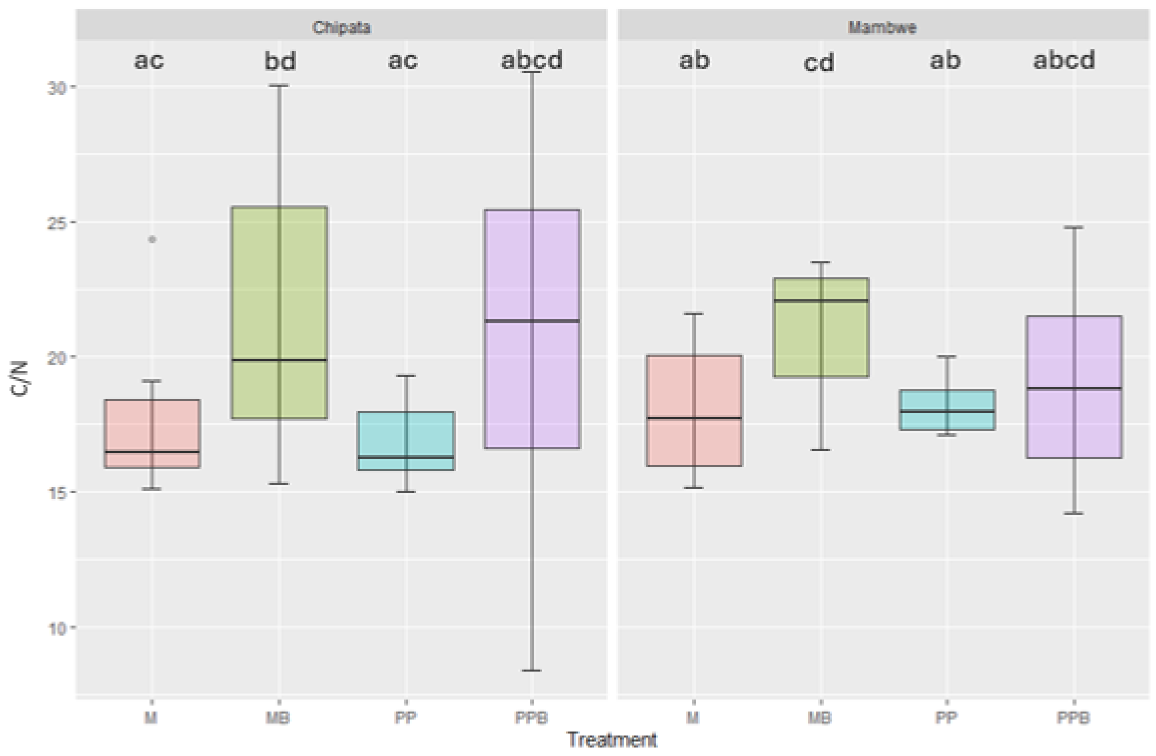

Figure 10: C/N ratio for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. Significant difference between treatments ($p<0.05$) M and MB in Chipata, and between MB and M and MB and PP in Mambwe.

3.4| Labile fraction and SOC

Tot C can be used as SOC as pH is low (Martinsen et al., 2017). $SOC_{tot\ C}$ also correlates well with the calculated SOC_{LOI} (appdx. D).

The measured HWEC did not differ significantly between the two districts or between the four treatments (figure 11). There is a strong significant correlation between HWEC and SOC (figure 12), which could indicate that SOC and HWEC can be quite dependent on each other. Changes to SOC content could be indicated by HWEC. This makes sense as HWEC measure the labile part of SOC. Ghani et al. (2003) found land use impact HWEC more than SOC. However, there is no significant differences for treatments for either HWEC or SOC.

Munere-Echeverri et al. (2020) found that data with biochar increased SOC, but it did not affect HWEC.

The hypothesis that biochar will increase SOC and HWEC is rejected.

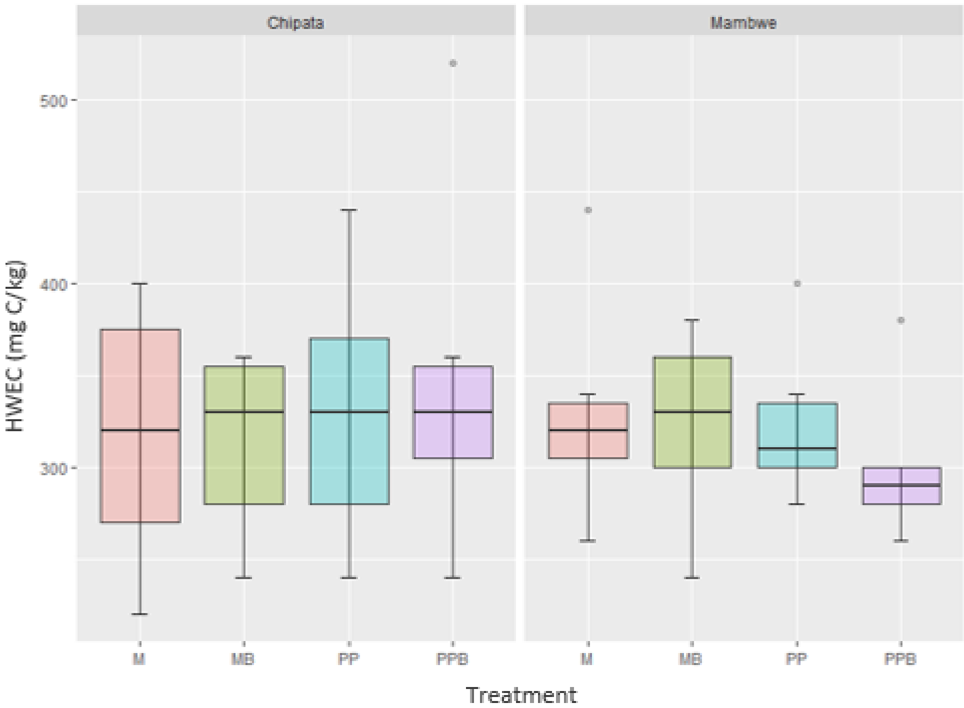

Figure 11: HWEC for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. No significant differences (p>0.05).

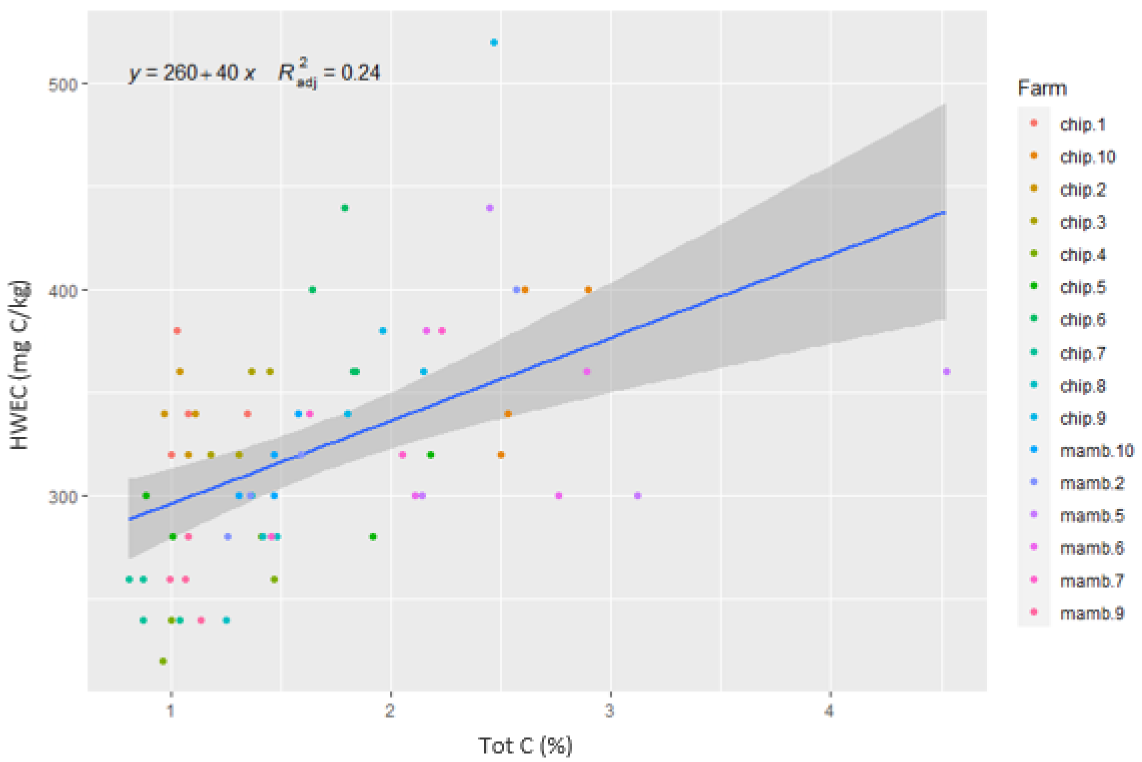

Figure 12: Relationship between HWEC and tot C for the 10 farms in Chipata and for the 6 farms in Mambw. p = 2.654e-05

SOC/clay ratio showed a clear significant difference between districts, with higher SOC/clay ratio in Mambwe (figure 14). Most of the SOC/clay ratio is above 1/10, which Dexter et al. (2008) determined is the approximate limit for SOC with clay particles when it comes to indicating good soil health. The European Soil Monitoring Law use 1/13 as an indicator of good soil health. Based on 1/10 ratio, most of the soils in Mambwe and about half of the soils in Chipata could be considered in good soil health. Using a ratio of 1/13 however most of the soils in Chipata would not be considered in good soil health and for half of the soils in Mambwe this is also the case. Rabot et al. (2024) found that acidic soils were consistently classified as healthy. Chipata has an acidic soil (figure 3), and according to Rabot et al. the soils in Chipata could be expected to be classified as healthy.

It's the passive, complex and stable SOC that's largely bound to clay particles. This makes SOC values highly site-dependent and strongly correlating with clay content as shown in figure xx.

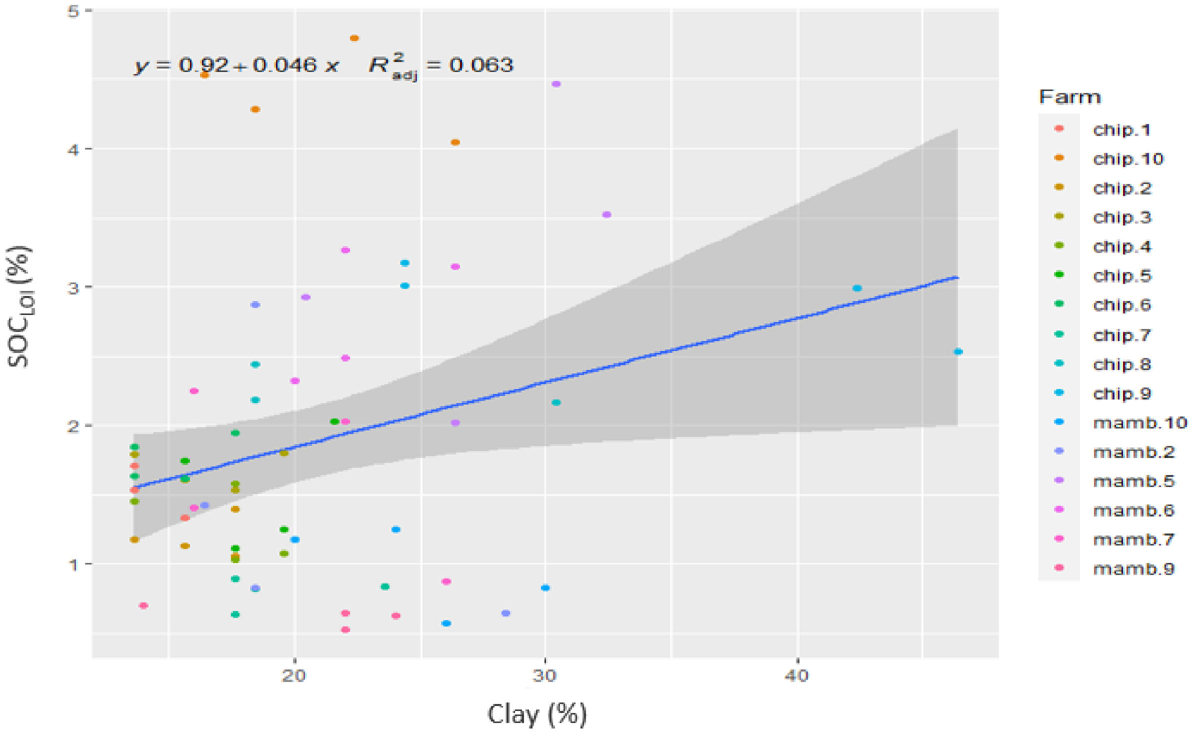

Figure 13: Relationship between clay and SOC_{LOI} for the 10 farms in Chipata and for the 6 farms in Mambw (p = 0.02588).

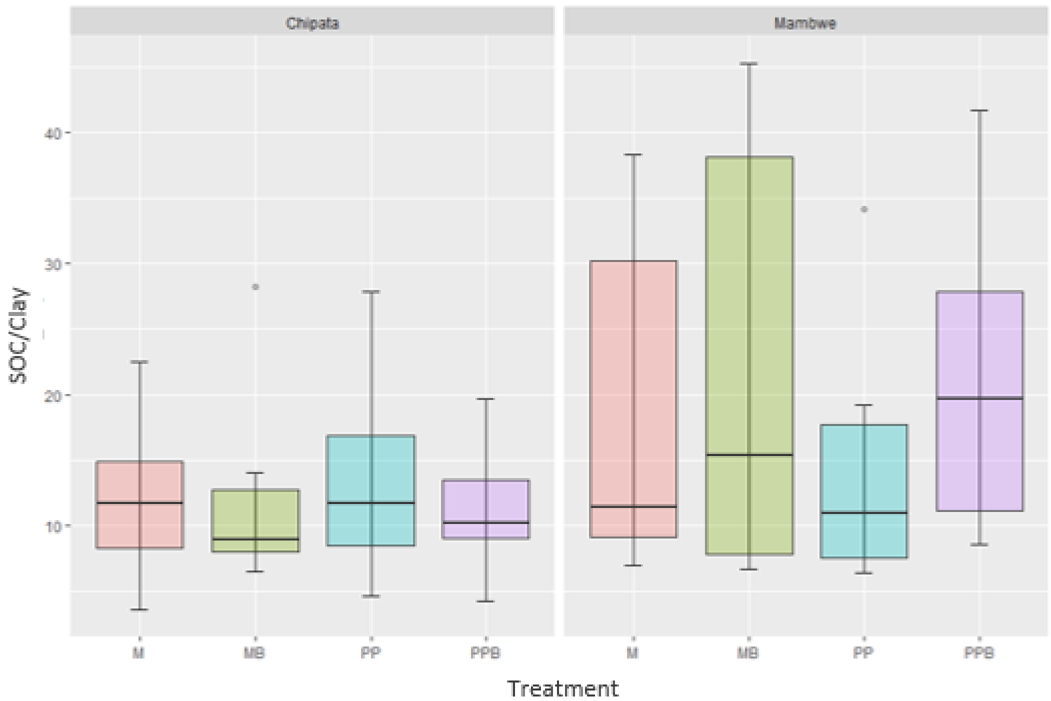

Figure 14: SOC/clay ratio for both districts and for the treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. Significant difference between districts ($p<0.05$), Mambwe had higher SOC/clay ratio. No significant difference between treatments ($p>0.05$).

3.3| N mineralisation

There is a net mineralization, primarily due to net nitrification, while some NH_4^+ is lost (figure 16). It indicates a net immobilization but could also be explained by further conversion of N to NO_3 by nitrification. As there is a positive net nitrification. Two of the values (appx. C) were under the detection level of the instrument (>0.32 mg/kg) and were assigned the value 0.16 mg/kg.

There are no significant differences between districts and between treatment for N mineralisation rate (figure 15).

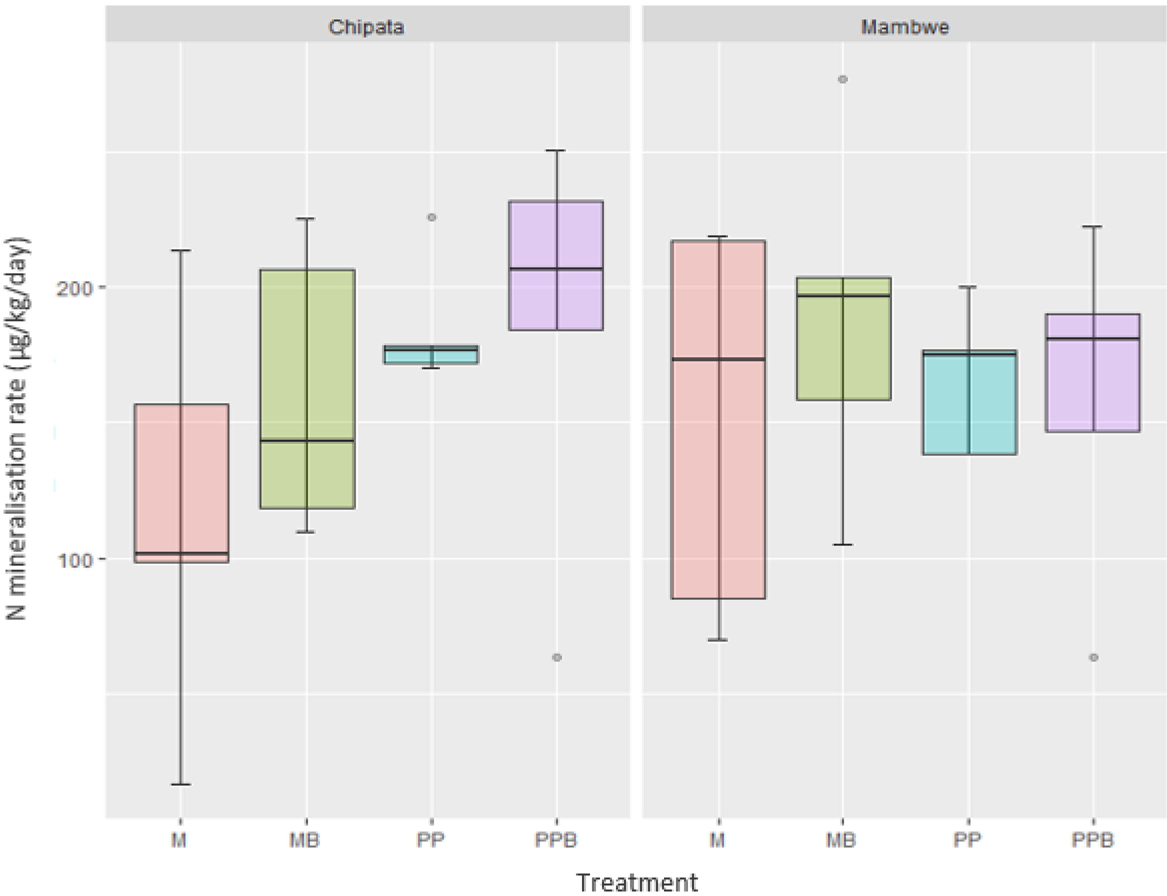

Figure 15: N mineralisation rate after 60 days of incubation. Treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. No significant difference between treatments (p>0.05).

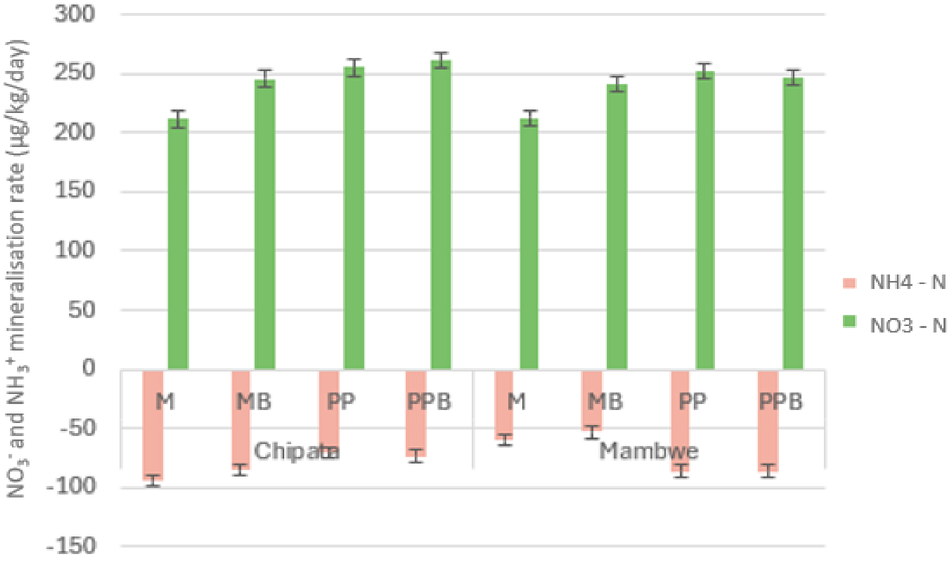

Figure 16: Mean amount of NO_3^- and NH_4^+ mineralisation rate after 60 days in the soil for each treatment in both districts. Net NO_3^- mineralisation rate, while NH_4^+ is lost. Error bars show standard deviation.

N mineralisation rate has negative correlation with HWEC, tot C and tot N (figure 17; figure 18; figure 19). This were a bit unexpected as Munera-Echeverri et al. (2020) found the correlation of N mineralisation rate and HWEC to be highly positive correlated. The N mineralization rate in Munera-Echeverria et al. study also had higher N mineralization rate than found here. The HWEC content is quite similar.

It could be an error source, potentially under incubation. Maybe the soil samples were water to late and were dryer than what they were observed as. It was important to water the samples, as it was crucial to ensure activity in the soil samples.

The hypothesis that biochar will increase N mineralisation rate is rejected.

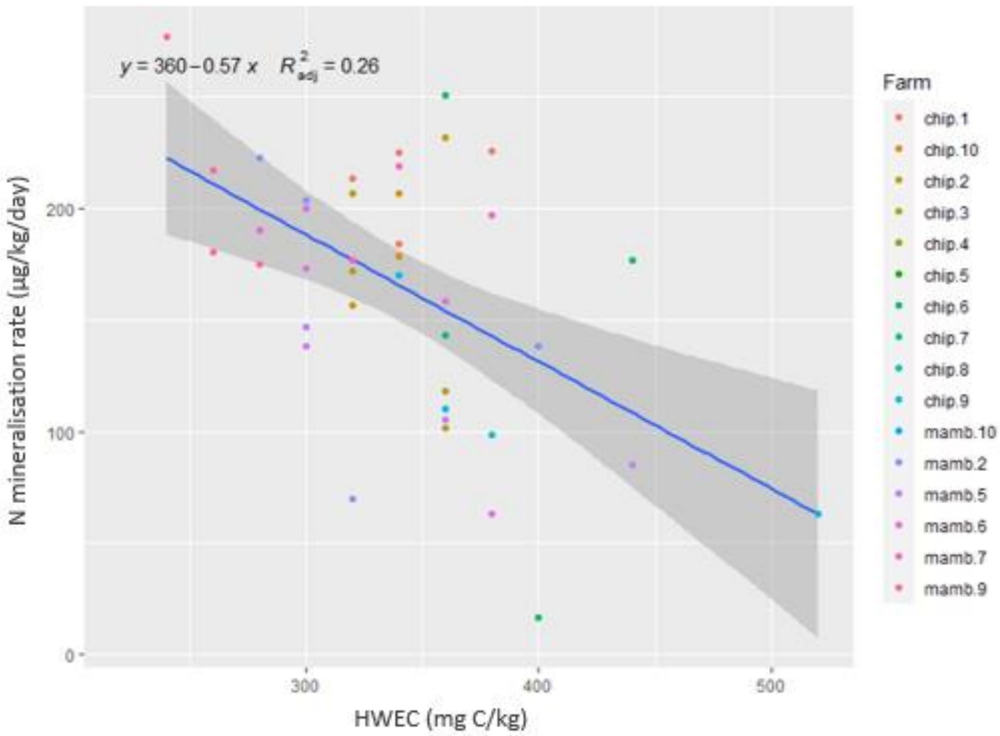

Figure 17: Relationship between HWEC and potential N mineralisation rate for the 10 farms in Chipata and for the 6 farms in Mambw.

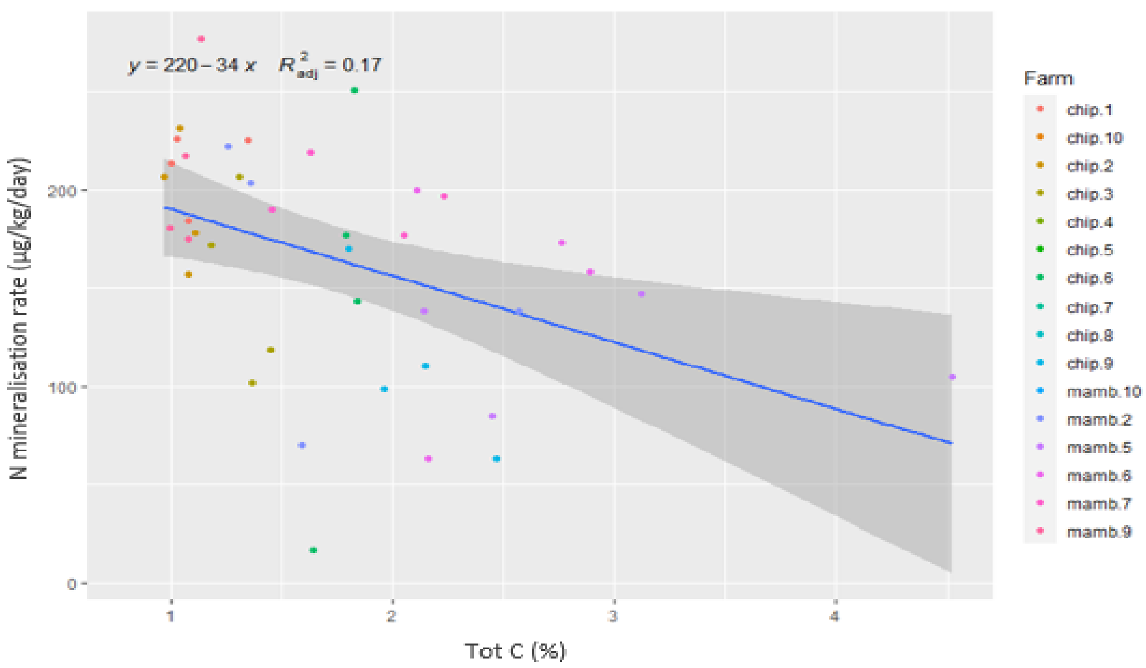

Figure 18: Relationship between tot C and potential N mineralisation rate for the 10 farms in Chipata and for the 6 farms in Mambw.

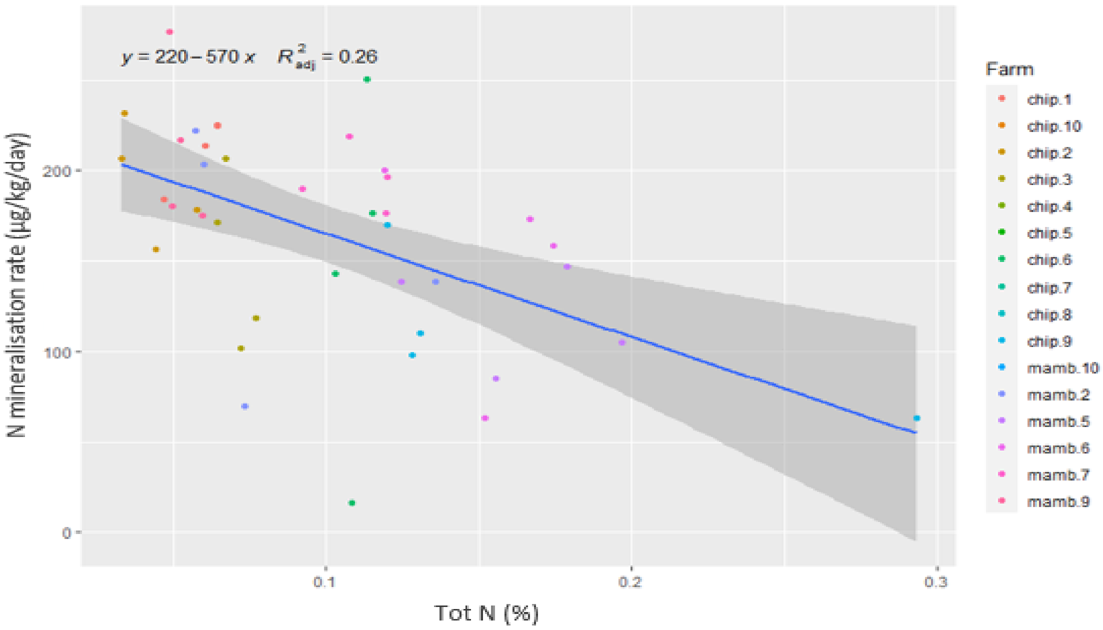

Figure 19: Relationship between tot N and potential N mineralisation rate for the 10 farms in Chipata and for the 6 farms in Mambw.

4| Study limitation and future work

In the plots with BC there were on several of the farms difficult to find the BC in the soil and on some of the farms there were very little BC to find. Combined with this and the sieving in the field that potential lead to some loss of BC, this could be why there is little rise in C content in plots with BC. There were also no BC left, so analyses on elemental composition of the BC could not be done.

There is socioeconomical differences between the districts. Farmers in Mambwe is used to presence of NGOs, which could be why the discussion of financial help were discussed under the farm training/meeting, whereas financial help was not discussed at al in Chipata. The farmers involved in the farm trial do not receive financial aid beyond fertiliser. Also, in Mambwe, the farmers took some of the fertilizer that were given from the project were used on fields of the farmers that was not a part of the farm trials. There are however no significant differences between total N and plant available N between the districts.

As the samples were collected after the first crop season for the farm trial, it will be interesting to see what future results will show. Especially the effect of pigeon pea rotation, as it was not included in this data, due to being the first cropping season. It will also be interesting to see if the expected increase in C content from the addition of BC will be more noticeable later.

5| Conclusion

The first cropping season of the farm trials in Chipata and Mambwe, did not give what was expected of the experiment. There was no significant difference between treatments when it came to the carbon and nitrogen content. Biochar did not increase the soils content of C as expected, it could not be seen in SOC, HWEC or SOM. Pigeon pea did not have a significant effect on the soils content of N or the plant available N. There was also no effect of biochar on N mineralisation rate. It was surprising that the N mineralisation went down with increasing HWEC (and tot C and tot N) as it was expected to increase. This could potentially be due to an error done under incubation of the soil samples.

There were a lot of significant differences between the two districts. Chipata were found to have lower pH than Mambwe. Both districts experienced increase in pH on the plots where BC were added. Mambwe had higher content of tot C, and thereby higher C/N rate. SOC/clay rate were also found to be higher in Mabwe, ass both clay and SOC content were higher for Mambwe.

None of the hypothesis that this thesis was to answer shown to be correct for the data collected. There is a need for more data.

References

Abebe, Y., Diriba, B. (2002). *Effect of Biomass Transfer of Cajanus Cajan With or Without Inorganic Fertilizer on BH-660 Hybrid Maize Variety at Bako, Western Oromia, Ethiopia*. Ethiopian Society of Soil science: Six conferences proceedings

Abebe, Z., Tadesse, S., & Tola, M. (2016). Multiple advantages of Pigeon Pea (Cajanas Cajan) in maize based cropping systems: Used as live stake for climbing bean with phosphorus rates and maize productivity enhancement in mono cropping areas. *J. Natural Sci. Reas., 6 (19): 58, 69*.

Abera, G., Wolde-Meskel, E., Bakken, L. R. (2012) Carbon and nitrogen mineralization dynamics in different soils of the tropics amended with legume residues and contrasting soil moisture content. *Biology and Fertility of Soils*, 48 (1): 51-66. DOI: 10.10007/s00374-011- 0607-8

Abiven, S., Andreas H., Martinsen, V., & Gerard, C. (2015). Biochar amendment increases maize root surface areas and branching: a socioeconomic study in Zambia. *Plant Soil*. DOI 10.1007/s11104-015-2533-2.

Adekanye, T., Dada, O., & Kolapo, J. (2022). Pyrolysis of maize cob at different temperatures for biochar production: Proximate, ultimate, and spectroscopic characterisation. *Research in Agricultural Engineering,* 68(1): 27-34 DOI: 10.17221/106/2020-RAE

Ae, N., Arihara, J., Okada, K., Yoshihara, T. & Johansen, C. (1990). Phosphorus uptake by pigeon pea and its role in cropping systems of the Indian subcontinent. *Science,* 248 (4954): 477-480. doi: 10.1126/science.248.4954.477.

Amelung, W., Bossio, D., de Vries, W. *(2020).* Towards a global-scale soil climate mitigation strategy. *Nat Commun,* (**11)**: 5427. DOI: 10.1038/s41467-020-18887-7

Anderson, C.R., Hamonts, K., Clough, T.J., Condron, L.M. (2014). Biochar does not afect soil N-transformations or microbial community structure under ruminant urine patches but does alter relative proportions of nitrogen cycling bacteria. *Agric Ecosyst Environ* 191:63–72. DOI: 10.1016/j.agee.2014.02.021

Arslan, A., McCarthy, N., Lipper, L., Astaw, S., Cattaneo, A. (2014) Adaption and intensity of adoption of conservation farming practices in Zambia. Agriculture, *Ecosystems and Environmnet*, 187: 72-86. DOI: 10.1016/j.agee.2013.08.017

Beyene, D., Kassa, S., Ampy, F., Asseffa, A., Gebremedhin, T., Berkum, P. (2004). Ethiopian soils harbor natural populations of rhizobia that form symbioses with common bean (Phaseolus vulgaris L.). *J Microbiol* 181:129–136

Biederman, L. A., Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-anlysis. *GCB Bionergy,* 5 (2): 202-214. DOI: 10.1111/gcbb.12037

Bodner, G., Loiskandl, W., Kaul, H.-P. (2007). Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agricultural Water Management,* doi: 10.1016/j.agwat.2007.06.010.

Brady, N. C. and R. R. Weil (2014). The Nature and Properties of Soil. Pearson New International Edition. Fifth Edition. Published by Pearson Prentice Hall.

Bremmer, J. M. & Mulvaney, C. S. (1982). Nitrogen-Total 1. Methods of soil analysis. Part 2 Agronomy 9. Chemical and microbiological properties, 2nd Edition. 2 ed. Madison, Wisconsin, USA: American Society of Agronomy,. pp. 595-624.

Burford, J.R., Bremner, J.M. (1975) Relationships between the denitrification capacities of soils and total, water-soluble, and readily decomposable soil organic matter. *Soil Biology & Biochemistry,* 7: 389–394.

Campbell, C.A., Biederbeck, V.O., McConkey, B.G., Curtin, D., Zentner, R.P. (1999). Soil quality-Effect of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt loam in South Western Saskatchewan. *Soil Biology & Biochemistry* 31: 1–7.

Chan, K. Y., van Zwiete, L., Meazaros, I., Downie, A. and Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research,* 45, 629-634. doi: 10.1071/SR07109

Chikowo, R. (2022). *Zambia*. Available: https://www.yieldgap.org/zambia (Accessed: 29.09. 2023).

Climate-smart Agriculture Sourcebook. 2 ed. Roma: FAO. Available at: https://www.fao.org/3/i7994e/i7994e.pdf (Accessed: 10. 06. 2023)

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. Doi: 10.1038/s4016-020-0114-x.

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 (2): 256-274.

Cornelissen, G., Shitumbanuma, V., and Martinsen, V., 2011. Improving crop yield and storing carbon End report phase 1; October 2011. Report NGI, 20100920-006-R, 52 p. Retrieved from: www.ngi.no/en/Project-pages/Biochar/News/Phase-2-report-1--- BioChar-Zambia/

Dakora, F.D., Keya, S.O. (1997). Contribution of legume nitrogen fixation to sustainable agriculture in Sub-Saharan Africa. Soil Biology and Biochemistry, 29 (5-6): 809-817. DOI: 10.1016/S0038-0717(96)00225-8

Dexter, A. R., Richard, G., Arrouays, D., Czyz, E. A., Jolivet, C., & Duval, O. (2008). Complexed organic matter controls soil physical properties. *Geoderma,* 144(3–4), 620–627. DOI:10.1016/j.geoderma.2008.01.022

Dobberman, R., Choudhary, B. K. (2023). Biofloc technology: A strategic way to water recycling in aquaculture, Organic Farming Global Perspective and Methods. Secon edition. Woodhead Publishing. DOI: https://doi.org/10.1016/C2021-0-01532-7

Dong, L., Martinsen, V., Wu, Y., Zheng, Y., Liang, C., Liu, Z. & Mulder, J. (2020). Effect of grazing exclusion and rotational grazing on labile soil organic carbon in north China. *European Journal of Soil Science*. doi: 10.1111/ejss.12952.

Doran, J. W., Parkin, T. B. (1994). Defining Soil Quality for Sustainable Environment, voleum 35.

Dury, S., Bendjebbar, P., Hainzelin, E., Giordano, T. & Bricas, N. (2019). *Food systems at risk. New trend and challenges*. Rome: FAO; CIRAD. Available at: https://www.fao.org/3/ca5724en/ca5724en.pdf (Accessed: 29.10.2023) FAO. (2017).

Faerge, J., Magid, J. (2004). Evaluating NUTMON nutrient balancing in Sub-Saharan Africa. *Nutrient Cycling in Agroecosystems*, 69 (2): 101-110. doi: 10.1023/b:Fres.0000029680.97610.51.

FAO. (2022). GIEWS – Global Information and Early Waring System. FAO. Available at https://www.fao.org/giews/countrybrief/country.jsp?code=ZMB (accessed: Feburary 19 2024).

Farooq and Siddique. (2015). *Conservational Agriculture*. Springer Cham Heidelberg New York Dodrecht London. Available at: https://doi.org/10.1007/978-3-319-11620-4 (Accessed: 10. 06. 2023)

Ferrarezi, R.S., Lin, X., Gonzalez Neira, A.C., Tabay Zambon, F., Hu, H., Wang, X., Huang, J.H., Fan, G. (2022). Substrate pH Influences the Nutrient Absorption and Rhizosphere Microbiome of Huanglongbing-Affected Grapefruit Plants. *Front Plant Sci.,* 13(13):856937. doi: 10.3389/fpls.2022.856937. PMID: 35646029; PMCID: PMC9141052.

Fischer, T. (1993). Einflub von Winterweizen und Winterroggen in Fruchtfolgen mit unterschiedlichem Getreideanteil auf die mikrobielle Biomasse und jahreszeitliche Kohlenstoffdynamik des Bodens. *Arch Acker Pflanzenbau Bodenkd* 37, 181–189.

Ghani, L., Dexter, M., Perrott, K. W. (2003) Hot water extractable carbon in soils: a sensitive measurement for determining impact of fertilisation, grazing and cultivation. *Soil Biology and Biochemistry,* 35 (9): 1231-1234. Doi:10.1016/S0038-0717(03)00186-X.

Ghodszad, L., Reyhanitabar, A., Maghsoodi, M. R., Lajayer, B. A., Chang, S. X. (2021). Biochar affects the fate of phosphorous in soil and water: A critical review. *Chemosphere*, 283: 131176. Doi: https://doi.org/10.1016/j.chemosphere.2021.131176 Page 11 of 12

Giller, K. E., Cadisch, G., Ehalioti, C., Adams, E., Sakala, W. D., Mafongoya, P. L. (1997). Building Soil Nitrogen Capital in Africa. SSSA Special Publication. Replenishing soil fertility in Africa, 51, doi: 10.2136/sssaspecpub51.c7

Glaser, B., Haumaier, L., Guggenberger, G., Zech, W. (2001). The ”terra petra” phenomenon: A model for sustainable agriculture in the humod tropics. *Nat. Wissenschaften* 88, 37-41.

Gregorich, E.G., Carter, M. R., Angers, D. A., Monreal, C. M., Ellert, B. H. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Science*. **74**(4): 367-385. https://doi.org/10.4141/cjss94-051

Haynes, R.J., Francis, G.S., 1993. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. Journal of Soil Science 44, 665–675

Hector V. and J.smith. (2007). Green Manure Crops: Pigeonpea: Sustainable Agriculture Green Manure Crops. Cooperative Extension services, College of Tropical and Human Resources, University of Haiwi at Manoa

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., & Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma,* 302, 111. DOI:10.1016/j.geoderma.2017.04.021

Keeney, D.R., Bremner, J.M. (1966). Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal*, 58, 498–503.fao

Khademalrasoul, A., Naveed, M., Heckrath, G., Kumari, K.G.I.D., Wollesen De Jonge, L., Elsgaard, L., Vogel, H.J., Iversen, B.V. (2014). Biochar effects on soil aggregate properties under no-till maize. *Soil Sci.*, 179 (6): 273–283. doi: 10.1097/ SS.0000000000000069.

Krogstad, T., Børresen, T. (2019). Field and laboratory methods for the analysis of soil: Norwegian University of Life Sciences.

Kumar K, Goh KM (2000) Nitrogen release from crop residues and organic amendments as affected by biochemical composition. *Communal Soil Science Plant Anual* 34:2441–2460

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science, 304(5677):1623-1627. DOI: 10.1126/science.109739

Magnone, D., Niasar, V. J., Bouwman, A. F., Beusen, A. H. W., van der Zee, S., Sattari, S. Z. (2019). Soil Chemistry Aspects of Predicting Future Phosphorus Requirements in Sub-Saharan Africa. *Journal of Advances in Modeling Earth Systems*, 11 (1): 327-337. doi: 10.1029/2018ms001367

Mapa, R.B., Gunasena, H.P.M. (1995). Effect of alley cropping on soil aggregate stability of a tropical Alfisol. *Agroforestry Systems*, 32: 237–245.

Mapiki, A., Phiri, S. (1995). Soil fertility constraints and management options in northern Zambia. In O.A. Yerokun & E. Mukhala (Eds.). A systems approach to long term soil productivity. Proceedings of a national soil productivity seminar. Department of Soil Science, University of Zambia, Lusaka, Zambia (7-10.02.1995)

Martinsen, V., V. Shitumbanuma, J. Mulder, C. Ritz, and G. Cornelissen. (2017). Effects of hand-hoe tilled conservation farming on soil quality and carbon stocks under on-farm conditions in Zambia. *Agriculture, Ecosystems & Environment* 241:168-178.

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M., Vanlauwe, B. (2017). Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review. Soil Research, 55: 425-434. DOI: 10.1071/SR16332

Mubaya, C., Njuki, J., Mutsvangwa, e. P., Mugabe, F. T. & Nanja, D. (2012). Climate variability and change or multiple stressors? Farmer perceptions regarding threats to livelihoods in Zimbabwe and Zambia. *Journal of environmental management*, 102: 9- 17. Doi: 10.1016/j.jenvman.2012.02.005.

Muchabi. J., Lungu, O.I and Mweetwa, A.M. (2014). Conservation Agriculture in Zambia; Effects on Selected Physical Properties and Biological Nitrogen Fixation in Soya Beans (Glycine max (L) Mer). *Sustainable Agriculture Research*; Vol 3, No 3. 28-36. DOI: 10.5539/sar.v3np28.

Mulenga, B. P., Wineman, A., Sitko, N. J. (2017). Climate Trends and Farmer's Perspective of Climate Change in Zambia. *Environment Management,* 59 ("): 291-306. DOI: 10.1007/s00267-0780-5

Munera-Echeverri, J. L., Martinsen, V., Strand L. T., Corneliseen, G., Mulder, J. (2020). Effcet of conservation farming and biochar addition on soil organic carbon quality, nitrogen mineralization, and crop productivity in a light textured Acrisol in the sub-humid tropics. *PLOS ONE*, 15(2): e0228717. https://doi.org/10.1371/journal.pone.0228717

Myaka, F.M., Sakala, W.D., Adu-Gyamfi, J.J. (2006). Yields and accumulations of N and P in farmer-managed intercrops of maize–pigeonpea in semi-arid Africa. *Plant Soil,* **285**: 207–220. https://doi.org/10.1007/s11104-006-9006-6

Nelson, D.W. and Sommers, L.E. (1996). Total Carbon, Organic Carbon and Organic Matter. Madison: *American Society of Agronomy*. DOI: 10.1007/978-3-319- 75076-7

Ngoma, H., Lupiya, P., Kabisa, M. & Hartley, F. (2021). Impacts of climate change on agriculture and household welfare in Zambia: and economy-wide analysis. *Climate Change*, 167: 1-20. Doi: 10.1007/s10584-021-03168-z

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W. and Niandou, M. A. S. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science*, 174: 105-112. doi: 10.1097/SS.0b013e3181981d9a

Lavallee, J. M., Soong, J.L., Cotrufo, M. F. (2019). Conceptuallizing soil organic matter into particulate and mineral-asscociated forms to address global changes in the 21st century. *Global Change Biology*, 26 (1): 26-273. DOI: 10.1111/gcb.14859

Li, S., Harris, S., Anandhi, A., Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: a review and data syntheses. *J Clean Prod* 215:890–902. https://doi.org/10.1016/j.jclepro.2019.01.106

Li X, Wang T, Chang SX, Jiang X, Song Y (2020) Biochar increases soil microbial biomass but has variable efects on microbial diversity: a meta-analysis. Sci Total Environ 749:141593. https://doi.org/10.1016/j.scitotenv.2020.141593

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agric Ecosyst Environ* 83:27–42

Powlson, D. S., Stirling, C. M., Thierfelder, D., White, R. P., Jat, M. L. (2016). Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agroecosystem? *Agriculture, Ecosystems and Environment*, 220: 164-174. DOI: 10.1016/j.agee.2016.01.005

Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, 156 (3-4): 75-83. doi: 10.1016/j.geoderma.2010.02.003.

Rabot, E., Saby, A.P.A., Martin, M.P., Barrè, P., Chenu, C., Cousin, I., Arrouays, D., Angers, D., Bispo, A. (2024). Relevance of the organic carbon to clay ratio as a national soil health indicator. *Geoderma*, 443. Doi: 10.1016/j.geoderma.2024.116829

Rao, M.R., Nair, P.K.R., Ong, C.K., 1998. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3–50.

Rao, MR, and Willey. RW. 1981. Stability performances of pigeon pea /sorghum intercrop system, pp. 306-317. In: Proc. Of the International Workshop on Intercropping, 1013 January 1979, ICRSAT,Hyderabad,India.ICRISAT.

Rumley, R. and Ong, C. (2007). Wetting Africa's Appetite: Conservational Agriculture is Turning Rainfall into Higher Crop Yields – and Catching on. RELMA Review Series, 3.

Sanderman, J., Hengl., T., Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. *PNAS*. DOI: 10.1073/pnas.1706103114

Schlatter, D. C., Kahl, K., Carlson, B., Huggins, D. R., Paulitz, T. (2018) Fungal community composition and diversity vary with soil depth and landscape position in a no-till wheat-based cropping system. *FEMS Microbiol Ecol* 94(7):fy098. https://doi.org/10.1093/femsec/fy098

Semb, G. (1985). Analyser av jord med forskjellig volumvekt. Sammenligning av analysetall basert på vektmengde og volum jord. https://nibio.brage.unit.no/nibio-xmlui/bitstream/handle/11250/2489724/431_012_Analyser%20av%20jord%20med%20forskjellig%20volumvekt.pdf?sequence=1

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., Reinhardt, J. (2016). Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, 17 (6): 1585- 1600. DOI: 10.1007/s10113-015-0910-2. Page 12 of 12

Shareef, T. M. E., Zhao, B., Filonchyk, M. (2018). Characterization of biochar derived from maize straw and corn cob and effects of their amendment on maize growth and loess soil properties. *Freseniou Environmental Bulletin*, 27 (5): 3678 – 3686. DOI:

Singh, H., Narthup, B. K., Rice, C. W., Prasad, P. V. V. (2022). Biochar application influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*, 4 (11): 8. DOI: 10.1007/s42773-022-00138-1

Sogbedji, J.M., van Es, H.M., Agbeko, K.L. (2006). Cover cropping and nutrient management strategies for maize production in Western Africa. *Agronomy Journal*, 98: 883 –889.

Sparling, G., Vojvodic-Vukovic, M., Schipper, L.A. (1998). Hot-water soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. *Soil Biology & Biochemistry* 30, 1469–1472.

Srinivasarao, C., Lal, R., Kundu, S. & Thakur, P. B. (2015). Conservation agriculture and soil carbon sequestration. In Conservation agriculture. *Springer*, pp. 479-524

Stern, R., Cooper, P. (2011). Assessing climate risk and climate change using rainfall data – a case study from Zambia. *Experimental Agriculture*, 47: 241-266. Doi: 10.1017/S0014479711000081

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J. & Prasad, P. V. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, 71 (2): 632-641. doi: 10.1093/jxb/erz446.

Smith, P., Cotrufo, M.F., Rumpel, C., Paustian, K., Kuikman, P.J., Elliott, J.A. *(*2015). Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *The Soil*, **1**, 665–685.

Taiz L., Zeiger E., Møller I.M., Murphy A. (2018). Plant Physiology and development. 6th ed. New York: Sinauer Associates. Umar, B.B, Aune, J.B., Johnsen, F.H., Lungu, O.I. (2011) Options for Improving Smallholder Conservation Agriculture in Zambia. *Journal of Agricultural Science*, 3(3): 50-62. DOI: 10.5539/jas.v3n3p50

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T. S., Lemanna, C. & Eyre, J. X. (2017). How climate-smart is conservation agriculture (CA)? - its potential to deliver on adaptation, mitigation, and productivity on smallholder farms in southern Africa. *Food Security*, 9: 537-560. Doi: 10.1007/s12571-017-0665-3.

Tully, K., Sullivan, C., Weil, R. & Sanchez, P. (2015). The state of soil degradation in SubSaharan Africa: Baselines, trajectories, and solutions. *Sustainability*, 7(6): 6523- 6552. Doi: 10.3390/su7066523

Umar, B. B. (2012). Reversing Agro-Based Land Degradation through Conservation Agriculture: Emerging Experiences from Zambia's Smallholder Farming Sector. *Sustainable Agriculture Research*, 2: 72-87. doi: 10.5539/sar.vln2p72.

Verheijen, F.G.A., Zhuravel., A., Silva, F.C., Amaro, A., Ben-Hur, M., Keizer, J. J. (2019). The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma*, 347: 194-202. Doi: 10.1016/j.geoderma.2019.03.044
Wang, X., J. Wang and J. Zhang (2012). "Comparisons of Three Methods for Organic and Inorganic Carbon in Calcareous Soils of Northwestern China." *PLOS ONE* 7(8): e44334.

Weigel, A., T. Eustice, R. v. Antwerpen, G. Naidoo and E. Schulz (2011). "Soil organic carbon (SOC) changes indicated by hot water extractable carbon (HWEC)." *Proceedings of the Annual Congress - South African Sugar Technologists' Association(*No.84): 210-222.

WorldPopulationReview. (2023). *Zambia population*. Available: https://worldpopulationreview.com/countries/zambia-population (Accessed: 29. 09. 2023)

Yadav, N. K., Kumar, V., Sharma, KR., Shoundhary, R. S., Butter, T. S., Singh, G., Kumar, M., Kumar, R. (2018). Biochar and their impacts on soil properties and crop productivity: a review. *Journal of Pharmacognosy and Phytochemistry*, 7 (4): 49-54. Available at: https://www.phytojournal.com/archives/2018/vol7issue4/PartB/7-3-678-801.pdf (Accessed)

Zaman, M. and Nguyen, M. L. (2010). Effect of lime or zeolite on N emissions from a pastoral soil treated with urine or nitrate-N fertilizer under field conditions. *Agriculture Ecosystem Environment*, 136: 254–261. doi: 10.1016/j.agee.2009.12.002

Appendix

Appendix A

Materials and methods

Table: Information about study area

District	Farm	Coordinates		Previous crop	Basine/ripline
		long	lat		
Chipata	Chip. 1	32.5838265	-13.5456568	Groundnuts	Ripline
	Chip. 2	32.5924220	-13.5137106	Maize	Ripline
	Chip. 3	32.5753135	-13.5272931	Maize	Ripline
	Chip. 4	32.5599424	-13.5256384	Maize	Ripline
	Chip. 5	32.5650302	-13.5452109	Maize	Ripline
	Chip. 6	32.5910456	-13.5793261	Groundnuts	Basin
	Chip. 7	32.5740254	-13.5636675	Groundnuts	Ripline
	Chip. 8	32.5911332	-13.5889814	Soybeans	Ripline
	Chip. 9	32.6010915	-13.5991617	Maize	Ripline
	Chip. 10	32.6312238	-13.5638458	Maize	Ripline
Mambwe	Mamb. 2	31.9816578	-13.2733580	Maize	Basin
	Mamb. 5	31.9795080	-13.2634423	Maize	Basin
	Mamb. 6	31.9690236	-13.2522162	Maize	Basin
	Mamb. 7	31.9376200	-13.2158071	Maize	Basin
	Mamb. 9	32.0238788	-13.2914854	Soybeans	Basin
	Mamb. 10	32.0100275	-13.2813436	Maize	Ripline

<u>Bulk density calculation</u>

$$V_{LAB}(kg/l) = m/10, \text{ 10 ml scoop}$$

$$\text{Sand} \quad VOL_{SAND} = 0.919 \cdot V_{LAB} + 0.231$$

Soil dry matter and loss on ignition calculations

$$\% \ dry\ matter = \frac{(m3-m1)}{m2} \cdot 100$$

$$\% \ loss\ on\ ignition = \frac{(m3-m4)}{(m3-m1)} \cdot 100$$

where *m1 = weight of crucible*
m2 = weight of soil sample before drying
m3 = weight of crucible with sample after drying
m4 = weight of crucible and sample after calcination

Clay content	**Correction figure**
5-9%	1
10-24%	2
25-39%	2.5
40-59%	3.5
>59%	4.5

Appendix B

Unpublished background data done at UNZA.

Table: different soil parameters such as Soil pH, Electrical conductivity (EC), Organic matter content (OM), Total Nitrogen (N), Available Phosphorus (P) and Particle size distribution. Soil samples collected in July 2022 before imposing Biochar treatments on previously farmed fields. Done by Miyanda Moombe at UNZA.

Treatment	Plot	pH 1:2.5 H2O	EC 1:5 mS/cm	OM Walkley & Black %	N Kjeldahl %	P Bray 1 mg/kg	Sand Hydrometer method %	Clay %	Silt %
PP	Chip 1.1	5.44	0.03	1.68627451	0.266	96.25	54	15.6	30.4
MB	Chip 1.2	5.63	0.032	2.630588235	0.2415	124.25	56	13.6	30.4
M	Chip 1.3	5.19	0.019	1.956078431	0.231	87.5	50	17.6	32.4
PPB	Chip 1.4	4.32	0.023	1.75372549	0.3045	94.5	56	13.6	30.4
PP	Chip 2.1	5.06	0.03	1.956078431	0.259	26.25	54	13.6	32.4
PPB	Chip 2.2	5.34	0.031	1.68627451	0.2135	66.5	52	17.6	30.4
M	Chip 2.3	4.63	0.026	1.888627451	0.175	45.5	60	17.6	22.4
MB	Chip 2.4	4.77	0.024	1.821176471	0.2205	52.5	54	15.6	30.4
PP	Chip 3.1	5.16	0.023	1.956078431	0.231	136.5	50	17.6	32.4
MB	Chip 3.2	5.22	0.028	2.158431373	0.196	111.125	56	13.6	30.4
M	Chip 3.3	5.08	0.03	2.090980392	0.3185	145.25	50	19.6	30.4
PPB	Chip 3.4	5.18	0.023	2.225882353	0.1575	186.375	54	15.6	30.4
MB	Chip 4.1	5.16	0.023	1.146666667	0.245	139.125	56	13.6	30.4
PPB	Chip 4.2	5.25	0.025	1.68627451	0.301	11.375	58	17.6	24.4
PP	Chip 4.3	4.54	0.028	1.551372549	0.217	77.875	56	17.6	26.4
M	Chip 4.4	5.01	0.019	1.75372549	0.189	61.25	60	19.6	20.4
MB	Chip 5.1	5.07	0.025	1.821176471	0.3465	98.875	54	15.6	30.4
PPB	Chip 5.2	4.54	0.025	1.551372549	0.1785	147	56	21.6	22.4
PP	Chip 5.3	5.35	0.027	0.674509804	0.245	88.375	52	17.6	30.4
M	Chip 5.4	5.5	0.03	1.618823529	0.224	117.25	50	19.6	30.4
M	Chip 6.1	5.05	0.01	2.158431373	0.245	11.9	56	13.6	30.4
PPB	Chip 6.2	5.17	0.011	2.900392157	0.14	39.375	52	15.6	32.4
PP	Chip 6.3	4.86	0.013	2.023529412	0.2135	22.225	60	13.6	26.4
MB	Chip 6.4	4.87	0.008	1.956078431	0.21	8.435	50	17.6	32.4
PP	Chip 7.1	5.27	0.016	1.416470588	0.2275	71.75	54	17.6	28.4
M	Chip 7.2	5.2	0.018	1.483921569	0.1925	82.25	49.6	18.4	32
PPB	Chip 7.3	5.23	0.02	1.146666667	0.2205	125.125	58	17.6	24.4
MB	Chip 7.4	5.18	0.013	1.214117647	0.1715	110.25	56	23.6	20.4
PPB	Chip 8.1	5.26	0.016	2.900392157	0.217	63.875	53.6	18.4	28
M	Chip 8.2	5.23	0.013	2.495686275	0.21	123.375	47.6	18.4	34
MB	Chip 8.3	5.27	0.019	3.035294118	0.259	152.25	33.6	30.4	36
PP	Chip 8.4	5.34	0.045	2.360784314	0.287	109.375	43.6	18.4	38
PPB	Chip 9.1	5.56	0.031	4.114509804	0.1995	125.125	23.6	42.4	34
MB	Chip 9.2	5.5	0.029	3.305098039	0.2695	303.625	43.6	24.4	32
PP	Chip 9.3	5.53	0.028	3.844705882	0.119	106.75	19.6	46.4	34
M	Chip 9.4	5.35	0.024	3.709803922	0.1645	110.25	45.6	24.4	30
M	Chip 10.1	5.34	0.027	5.868235294	0.168	9.065	57.6	16.4	26

PPB	Chip 10.2	6.12	0.09	5.12627451	0.147	1.855	59.6	18.4	22
PP	Chip 10.3	5.36	0.013	4.519215686	0.161	1.33	53.6	22.4	24
MB	Chip 10.4	5.58	0.03	4.519215686	0.154	7.595	29.6	26.4	44
PPB	Mamb 2.1	6.01	0.026	4.384313725	0.1225	39.375	45.6	18.4	36
M	Mamb 2.2	6.23	0.062	4.721568627	0.1435	54.25	53.6	16.4	30
MB	Mamb 2.3	6.77	0.117	3.305098039	0.1225	34.125	33.6	28.4	38
PP	Mamb 2.4	5.76	0.02	4.181960784	0.14	29.75	27.6	18.4	54
MB	Mamb 3.1	6.15	0.036	2.360784314	0.1211	41.125	43.6	20.4	36
M	Mamb 3.2	6.07	0.051	2.495686275	0.119	125.125	33.6	26.4	40
PPB	Mamb 3.3	6.42	0.052	3.305098039	0.21	62.125	53.6	22.4	24
PP	Mamb 3.4	6.36	0.11	3.102745098	0.161	59.5	51.6	18.4	30
M	Mamb 5.1	6.21	0.037	4.114509804	0.1505	63.875	55.6	20.4	24
PPB	Mamb 5.2	6.33	0.049	6.070588235	0.231	59.5	37.6	32.4	30
PP	Mamb 5.3	6.26	0.033	6.272941176	0.056	96.25	45.6	26.4	28
MB	Mamb 5.4	6.46	0.047	5.868235294	0.168	73.5	35.6	30.4	34
M	Mamb 6.1	6.3	0.064	4.451764706	0.147	75.25	37.6	26.4	36
PP	Mamb 6.2	5.8	0.032	4.721568627	0.14	136.5	46	22	32
PPB	Mamb 6.3	6.11	0.043	5.19372549	0.1645	57.75	56	20	24
MB	Mamb 6.4	6.16	0.058	4.721568627	0.1785	79.625	60	22	18
M	Mamb 7.1	6.14	0.039	4.181960784	0.14	32.375	56	16	28
PP	Mamb 7.2	5.92	0.032	2.765490196	0.161	14	60	16	24
PPB	Mamb 7.3	6.17	0.046	3.170196078	0.1295	31.5	54	26	20
MB	Mamb 7.4	6.07	0.045	4.114509804	0.133	62.125	56	22	22
PPB	Mamb 9.1	6.35	0.044	1.618823529	0.091	170.625	56	22	22
MB	Mamb 9.2	6.44	0.066	2.563137255	0.098	53.375	60	14	26
M	Mamb 9.3	6.45	0.055	1.821176471	0.1085	46.375	38	24	38
PP	Mamb 9.4	6.24	0.038	2.158431373	0.0945	46.375	48	22	30
MB	Mamb 10.1	6.22	0.033	3.50745098	0.14	21.875	48	26	26
PPB	Mamb 10.2	5.89	0.052	2.495686275	0.112	115.5	56	20	24
M	Mamb 10.3	5.38	0.12	2.495686275	0.126	117.25	40	30	30
PP	Mamb 10.4	5.74	0.058	2.293333333	0.1435	67.375	46	24	30

Table: different soil parameters such as pH, organic matter (OM), nitrogen (N), phosphorus (P), potassium (K) and cation exchange capacity (CEC). Soil analysis results done in July of2023 by Gideon Musukwa at UNZA.

Lab no.	**Sample Id**	**pH 1:2.5 H2O**	**OM (%) Walkley-Black**	**N (%) Kjeldahl**	**P (mg/kg) Bray 1**	**K (cmol/kg) 1N NH4OAc**	**CEC (cmol/kg) Leaching method**
2023372	Chip 1	5.81	0.48	0.19	25.57	0.88	7.6
2023373	Chip 2	5.45	0.88	0.09	61.71	0.52	19.9
2023374	Chip 3	5.44	2.32	0.12	51.83	0.57	23.4
2023375	Chip 4	5.52	2.4	0.1	49.37	0.52	11.6
2023376	Chip 5	5.37	2.08	0.09	49.37	0.31	17.8
2023377	Chip 6	5.18	0.56	0.09	33.07	0.19	21.4
2023378	Chip 7	5.4	5.52	0.04	34.06	0.52	19
2023379	Chip 8	5.47	1.36	0.14	54.3	0.67	14.5
2023380	Chip 9	5.72	1.52	0.12	54.3	1.6	17.7
2023381	Chip 10	5.53	1.28	0.14	24.19	0.87	15.8
2023382	Mamb 1	6.16	1.76	0.07	51.83	0.85	20.9
2023383	Mamb 2	6.81	1.76	0.08	31.3	0.51	17.6
2023384	Mamb 3	6.36	1.92	0.03	31.79	0.77	18
2023385	Mamb 4	6.22	2.72	0.07	15.8	1.99	39
2023386	Mamb 5	6.5	0.72	0.09	32.93	1.72	24
2023387	Mamb 6	6.46	4.56	0.13	20.78	8.3	37
2023388	Mamb 7	6.35	1.92	0.12	27.15	0.82	45
2023389	Mamb 8	6.55	3.36	0.04	32.58	0.42	30.5
2023390	Mamb 9	6.63	1.36	0.09	30.61	1.19	29.3
2023391	Mamb 10	6.16	1.68	0.13	28.63	0.84	26.5

Appendix C

Data from analyses done at NMBU.

Table: soil data for the 64 samples. Analyses done at NMBU.

sample	ID	District	Farm	Treatment	pH_H2O	pH_CaCl2	tot C %	tot N %	C/N	LOI %	SOC_{LOI} %	SOC/Clay	HWEC (mg C/kg)
1	chip1.1	Chipata	chip.1	PP	5.05	5.28	1.03	0.06	16.0	2.29	1.3282	11.745219	380
2	chip1.2	Chipata	chip.1	MB	5.37	5.23	1.35	0.06	20.9	2.94	1.7052	7.975604	340
3	chip1.3	Chipata	chip.1	M	4.77	5.22	1.00	0.06	16.6	2.41	1.3978	12.591215	320
4	chip1.4	Chipata	chip.1	PPB	5.2	5.61	1.08	0.05	23.1	2.64	1.5312	8.8819227	340
5	chip2.1	Chipata	chip.2	PP	5.26	5.3	1.11	0.06	19.3	2.02	1.1716	11.608057	340
6	chip2.2	Chipata	chip.2	PPB	5.03	5.42	1.04	0.03	30.6	1.82	1.0556	16.672982	360
7	chip2.3	Chipata	chip.2	M	5.13	4.96	1.08	0.04	24.4	2.4	1.392	12.643678	320
8	chip2.4	Chipata	chip.2	MB	4.99	5.22	0.97	0.03	29.4	1.95	1.131	13.793103	340
9	chip3.1	Chipata	chip.3	PP	4.85	4.89	1.18	0.06	18.4	2.65	1.537	11.450878	320
10	chip3.2	Chipata	chip.3	MB	5.09	4.82	1.45	0.08	18.8	3.09	1.7922	7.5884388	360
11	chip3.3	Chipata	chip.3	M	4.65	4.58	1.37	0.07	19.0	3.11	1.8038	10.86595	360
12	chip3.4	Chipata	chip.3	PPB	4.94	5.17	1.31	0.07	19.6	2.77	1.6066	9.7099465	320
13	chip4.1	Chipata	chip.4	MB	4.73	5.08	1.47	0.05	30.1	2.5	1.45	9.3793103	260
14	chip4.2	Chipata	chip.4	PPB	4.66	5.11	1.41	0.05	25.8	2.72	1.5776	11.156187	280
15	chip4.3	Chipata	chip.4	PP	4.33	5.17	1.00	0.06	16.8	1.77	1.0266	17.14397	240
16	chip4.4	Chipata	chip.4	M	4.5	4.75	0.96	0.06	16.3	1.85	1.073	18.266542	220
17	chip5.1	Chipata	chip.5	MB	5.15	5.14	1.92	0.07	26.6	3.01	1.7458	8.9357315	280
18	chip5.2	Chipata	chip.5	PPB	5.13	5.36	2.18	0.08	27.1	3.49	2.0242	10.670882	320
19	chip5.3	Chipata	chip.5	PP	5.02	5.33	1.01	0.06	15.8	1.92	1.1136	15.804598	280
20	chip5.4	Chipata	chip.5	M	4.46	4.8	0.89	0.05	16.4	2.16	1.2528	15.644955	300
21	chip6.1	Chipata	chip.6	M	5.07	5.2	1.64	0.11	15.1	2.82	1.6356	8.3149914	400
22	chip6.2	Chipata	chip.6	PPB	6.14	6.22	1.83	0.11	16.2	2.78	1.6124	9.6750186	360
23	chip6.3	Chipata	chip.6	PP	5.75	5.75	1.79	0.12	15.5	3.18	1.8444	7.3736717	440

24	chip6.4	Chipata	chip.6	MB	4.98	5.36	1.84	0.10	17.9	3.36	1.9488	9.0311987	360
25	chip7.1	Chipata	chip.7	PP	5.01	5.39	0.81	0.04	19.3	1.09	0.6322	27.839291	260
26	chip7.2	Chipata	chip.7	M	4.5	4.76	0.88	0.05	19.1	1.41	0.8178	22.499389	260
27	chip7.3	Chipata	chip.7	PPB	5.09	5.1	1.04	0.04	24.5	1.54	0.8932	19.704433	240
28	chip7.4	Chipata	chip.7	MB	5.02	4.88	0.88	0.04	22.5	1.44	0.8352	28.256705	240
29	chip8.1	Chipata	chip.8	PPB	5.22	5.41	1.37	0.08	16.3	3.77	2.1866	8.4148907	300
30	chip8.2	Chipata	chip.8	M	4.56	4.89	1.25	0.07	16.7	3.76	2.1808	8.4372707	240
31	chip8.3	Chipata	chip.8	MB	5.07	5.18	1.48	0.10	15.3	3.74	2.1692	14.014383	280
32	chip8.4	Chipata	chip.8	PP	4.34	5.32	1.42	0.09	15.9	4.21	2.4418	7.5354247	280
33	chip9.1	Chipata	chip.9	PPB	5.28	5.44	2.47	0.29	8.4	5.15	2.987	14.194844	520
34	chip9.2	Chipata	chip.9	MB	4.85	5.07	2.15	0.13	16.4	5.19	3.0102	8.1057737	360
35	chip9.3	Chipata	chip.9	PP	4.88	5.18	1.80	0.12	15.0	4.36	2.5288	18.348624	340
36	chip9.4	Chipata	chip.9	M	4.88	5.06	1.96	0.13	15.3	5.47	3.1726	7.6908529	380
37	chip10.1	Chipata	chip.10	M	4.76	5.04	2.61	0.17	15.8	7.82	4.5356	3.6158391	400
38	chip10.2	Chipata	chip.10	PPB	4.7	5.2	2.53	0.15	17.3	7.39	4.2862	4.2928468	340
39	chip10.3	Chipata	chip.10	PP	4.75	5.22	2.90	0.17	16.6	8.27	4.7966	4.6699746	400
40	chip10.4	Chipata	chip.10	MB	4.6	5.2	2.50	0.14	17.7	6.97	4.0426	6.5304507	320
41	mamb2.1	Mambwe	mamb.2	PPB	5.48	6.39	1.26	0.06	22.0	1.42	0.8236	22.340942	280
42	mamb2.2	Mambwe	mamb.2	M	5.31	5.45	1.59	0.07	21.6	2.46	1.4268	11.494253	320
43	mamb2.3	Mambwe	mamb.2	MB	5.48	6.31	1.36	0.06	22.7	1.11	0.6438	44.113079	300
44	mamb2.4	Mambwe	mamb.2	PP	5.6	5.53	2.57	0.14	19.0	4.95	2.871	6.4089168	400
47	mamb5.1	Mambwe	mamb.5	M	5.39	5.91	2.45	0.16	15.8	5.04	2.9232	6.9786535	440
48	mamb5.2	Mambwe	mamb.5	PPB	5.95	6.06	3.12	0.18	17.5	6.07	3.5206	9.2029768	300
49	mamb5.3	Mambwe	mamb.5	PP	5.69	6.26	2.14	0.12	17.2	3.48	2.0184	13.079667	300
50	mamb5.4	Mambwe	mamb.5	MB	5.42	5.85	4.52	0.20	23.0	7.71	4.4718	6.7981573	360
51	mamb6.1	Mambwe	mamb.6	M	5.46	5.7	2.76	0.17	16.5	5.43	3.1494	8.3825491	300
52	mamb6.2	Mambwe	mamb.6	PP	6.17	6.24	2.11	0.12	17.7	4.28	2.4824	8.8623912	300
53	mamb6.3	Mambwe	mamb.6	PPB	6.26	6.58	2.16	0.15	14.2	4	2.32	8.6206897	380
54	mamb6.4	Mambwe	mamb.6	MB	6.11	5.97	2.89	0.17	16.6	5.63	3.2654	6.7373063	360
55	mamb7.1	Mambwe	mamb.7	M	6.18	6.09	1.63	0.11	15.2	2.43	1.4094	11.352349	340

56	mamb7.2	Mambwe	mamb.7	PP	6.12	5.9	2.05	0.12	17.1	3.87	2.2446	7.1282188	320
57	mamb7.3	Mambwe	mamb.7	PPB	6.23	6.21	1.46	0.09	15.9	1.51	0.8758	29.687143	280
58	mamb7.4	Mambwe	mamb.7	MB	6.34	6.11	2.23	0.12	18.6	3.5	2.03	10.837438	380
61	mamb9.1	Mambwe	mamb.9	PPB	6.36	6.25	1.00	0.05	20.2	0.91	0.5278	41.682455	260
62	mamb9.2	Mambwe	mamb.9	MB	6.79	6.72	1.14	0.05	23.5	1.21	0.7018	19.948703	240
63	mamb9.3	Mambwe	mamb.9	M	6.22	5.53	1.07	0.05	20.5	1.08	0.6264	38.314176	260
64	mamb9.4	Mambwe	mamb.9	PP	6.5	6.45	1.08	0.06	18.2	1.11	0.6438	34.172103	280
65	mamb10.1	Mambwe	mamb.10	MB	6.16	5.46	1.31	0.06	21.4	0.99	0.5742	45.28039	300
66	mamb10.2	Mambwe	mamb.10	PPB	6.22	6.07	1.47	0.06	24.8	2.03	1.1774	16.986581	300
67	mamb10.3	Mambwe	mamb.10	M	6.17	5.87	1.47	0.08	18.8	1.42	0.8236	36.425449	320
68	mamb10.4	Mambwe	mamb.10	PP	6.42	6.31	1.58	0.08	20.0	2.15	1.247	19.246191	340

*Table: N mineralisation analysis done for 40 samples in three sets. * under limit of detection for FIA (>0.32 mg/kg), were given 0.16 mg/kg)*

id	treatment	NO3-N mg/kg	NO3-N day 30 mg/kg	NO3-N day 60 mg/kg	NO3-N rate mg/kg/day	NO3-N µg/kg/day	NH4-N mg/kg	NH4-N day 30 mg/kg	NH4-N day 60 mg/kg	NH4-N min.rate mg/kg/day	NH4-N min.rate µg/kg/day	N.min. rate mg/kg/day	N.min.rate µg/kg/day
chip 1.1	PP	0.16*	8.44	16.84	0.28067	280.667	16.84	-0.8	-3.3	-0.055	-55	0.22567	225.667
chip 1.2	MB	1.9	9.1	17.1	0.285	285	17.1	-2.8	-3.6	-0.06	-60	0.225	225
chip 1.3	M	0.58	11.42	16.42	0.27367	273.667	16.42	-1.1	-3.6	-0.06	-60	0.21367	213.667
chip 1.4	PPB	0.16	8.54	14.84	0.24733	247.333	14.84	-3	-3.8	-0.06333	-63.3333	0.184	184
chip 2.1	PP	1.9	9.1	15.1	0.25167	251.667	15.1	-1.9	-4.4	-0.07333	-73.3333	0.17833	178.333
chip 2.2	PPB	1.5	10.5	17.5	0.29167	291.667	17.5	-2.8	-3.6	-0.06	-60	0.23167	231.667
chip 2.3	M	3.7	4.9	13.3	0.22167	221.667	13.3	-1.4	-3.9	-0.065	-65	0.15667	156.667
chip 2.4	MB	2.6	8.4	16.4	0.27333	273.333	16.4	-3.2	-4	-0.06667	-66.6667	0.20667	206.667
chip 3.1	PP	1.8	10.2	15.2	0.25333	253.333	15.2	-2.4	-4.9	-0.08167	-81.6667	0.17167	171.667
chip 3.2	MB	4.8	3.8	14.2	0.23667	236.667	14.2	-6.3	-7.1	-0.11833	-118.333	0.11833	118.333
chip 3.3	M	5.4	5.6	11.6	0.19333	193.333	11.6	-3	-5.5	-0.09167	-91.6667	0.10167	101.667
chip 3.4	PPB	2.6	9.4	16.4	0.27333	273.333	16.4	-3.2	-4	-0.06667	-66.6667	0.20667	206.667
chip 6.1	M	7.4	1.2	9.6	0.16	160	9.6	-6.1	-8.6	-0.14333	-143.333	0.01667	16.6667
chip 6.2	PPB	0.87	10.13	18.13	0.30217	302.167	18.13	-2.3	-3.1	-0.05167	-51.6667	0.2505	250.5
chip 6.3	PP	1.6	10.4	15.4	0.25667	256.667	15.4	-2.3	-4.8	-0.08	-80	0.17667	176.667
chip 6.4	MB	5.3	3.3	13.7	0.22833	228.333	13.7	-4.3	-5.1	-0.085	-85	0.14333	143.333
chip 9.1	PPB	5.7	5.3	11.3	0.18833	188.333	11.3	-5	-7.5	-0.125	-125	0.06333	63.3333
chip 9.2	MB	6.7	5.3	12.3	0.205	205	12.3	-4.9	-5.7	-0.095	-95	0.11	110
chip 9.3	PP	3.1	5.5	13.9	0.23167	231.667	13.9	-1.2	-3.7	-0.06167	-61.6667	0.17	170
chip 9.4	M	6.5	4.5	12.5	0.20833	208.333	12.5	-5.8	-6.6	-0.11	-110	0.09833	98.3333
mamb 2.1	PPB	0.36	11.64	16.64	0.27733	277.333	16.64	-0.8	-3.3	-0.055	-55	0.22233	222.333
mamb 2.2	M	7.7	0.9	11.3	0.18833	188.333	11.3	-6.3	-7.1	-0.11833	-118.333	0.07	70
mamb 2.3	MB	0.49	10.51	16.51	0.27517	275.167	16.51	-1.8	-4.3	-0.07167	-71.6667	0.2035	203.5
mamb 2.4	PP	3.3	8.7	15.7	0.26167	261.667	15.7	-6.6	-7.4	-0.12333	-123.333	0.13833	138.333
mamb 5.1	M	10	-1.4	7	0.11667	116.667	7	0.6	-1.9	-0.03167	-31.6667	0.085	85
mamb 5.2	PPB	6.0	5	13	0.21667	216.667	13	-3.4	-4.2	-0.07	-70	0.14667	146.667

mamb 5.3	PP	5.0	7	12	0.2	200	12	-1.2	-3.7	-0.06167	-61.6667	0.13833	138.333
mamb 5.4	MB	11	-2.4	8	0.13333	133.333	8	-0.9	-1.7	-0.02833	-28.3333	0.105	105
mamb 6.1	M	3.5	7.5	13.5	0.225	225	13.5	-0.6	-3.1	-0.05167	-51.6667	0.17333	173.333
mamb 6.2	PP	3.6	8.4	15.4	0.25667	256.667	15.4	-2.6	-3.4	-0.05667	-56.6667	0.2	200
mamb 6.3	PPB	4.7	3.9	12.3	0.205	205	12.3	-6	-8.5	-0.14167	-141.667	0.06333	63.3333
mamb 6.4	MB	5.1	5.9	13.9	0.23167	231.667	13.9	-3.6	-4.4	-0.07333	-73.3333	0.15833	158.333
mamb 7.1	M	0.16*	11.84	15.84	0.264	264	15.84	-0.2	-2.7	-0.045	-45	0.219	219
mamb 7.2	PP	3.6	5	15.4	0.25667	256.667	15.4	-4	-4.8	-0.08	-80	0.17667	176.667
mamb 7.3	PPB	1.3	9.7	15.7	0.26167	261.667	15.7	-1.8	-4.3	-0.07167	-71.6667	0.19	190
mamb 7.4	MB	3.3	8.7	15.7	0.26167	261.667	15.7	-3.1	-3.9	-0.065	-65	0.19667	196.667
mamb 9.1	PPB	0.66	7.94	16.34	0.27233	272.333	16.34	-3	-5.5	-0.09167	-91.6667	0.18067	180.667
mamb 9.2	MB	0.88	10.12	18.12	0.302	302	18.12	-0.7	-1.5	-0.025	-25	0.277	277
mamb 9.3	M	0.88	11.12	16.12	0.26867	268.667	16.12	-0.6	-3.1	-0.05167	-51.6667	0.217	217
mamb 9.4	PP	1.9	6.7	17.1	0.285	285	17.1	-5.8	-6.6	-0.11	-110	0.175	175

Table: To show contamination of NH_4^+ in the blanks.

259-2023	FIA	
14.02.2024	2MKCl	
LOD in w/W	0,095164332	0,07739186
LOQ in w/W	0,317214439	0,257972867
	NO3-N	**NH4-N**
	mg/kg	**mg/kg**
BLANK	<LD	0,52
BLANK	<LD	0,57
BLANK	<LD	0,57
BLANK	<LD	0,53
1	<0,32	4,4
2	1,9	5,1
3	0,58	4,7
4	<0,32	5,3
5	1,9	5,5
6	1,5	5,1
7	3,7	5,0
8	2,6	5,5
9	1,8	6,0
10	4,8	8,6
11	5,4	6,6
12	2,6	5,5
13	7,4	9,7
14	0,87	4,6
15	1,6	5,9
16	5,3	6,6
17	5,7	8,6
18	6,7	7,2
19	3,1	4,8
20	6,5	8,1
21	0,36	4,4
22	7,7	8,6
23	0,49	5,4
24	3,3	8,9
25	10	3,0
26	6,0	5,7
27	5,0	4,8
28	11	3,2
29	3,5	4,2
30	3,6	4,9
31	4,7	9,6
32	5,1	5,9
33	<0,32	3,8
34	3,6	6,3

35	1,3	5,4
36	3,3	5,4
37	0,66	6,6
38	0,88	3,0
39	0,88	4,2
40	1,9	8,1
41	8,6	3,6
42	11	2,3
43	12	3,0
44	8,7	3,9
45	8,0	2,7
46	7,5	1,1
47	9,9	0,98
48	8,1	1,4
49	17	1,4
50	23	1,2
51	13	3,9
52	17	0,84
53	17	1,4
54	10	1,3
55	12	0,92
56	14	1,1
57	25	1,2
58	22	1,0
59	15	1,3
60	23	1,1
61	8,0	0,94
62	23	1,3
63	8,6	0,97
64	23	2,5
65	25	1,1
66	19	0,72
67	15	0,57
68	22	1,0
69	14	0,62
70	12	0,74
71	19	0,60
72	19	0,89
73	12	0,68
74	16	0,69
75	12	0,58
76	15	0,65
77	8,1	0,65
78	7,3	0,67
79	8,7	1,1
80	9,4	0,63

81	17	1,1
82	19	1,5
83	20	1,3
84	15	1,4
85	15	1,1
86	14	2,9
87	14	1,1
88	13	1,2
89	20	0,9
90	26	0,73
91	26	0,95
92	22	1,2
93	23	1,3
94	12	2,6
95	14	0,82
96	21	1,1
97	28	0,66
98	25	0,96
99	19	0,96
100	28	0,77
101	11	0,63
102	26	1,2
103	14	0,67
104	23	1,7
105	17	0,61
106	21	0,56
107	20	0,79
108	23	0,99
109	14	1,4
110	16	1,2
111	20	0,69
112	21	1,2
113	16	0,66
114	17	0,59
115	15	0,57
116	17	0,53
117	12	0,61
118	9,2	0,61
119	12	0,77
120	12	0,57
kontroll jord "B"	7,5	25
kontroll jord "B"	7,5	25
kontroll jord "A"	7,7	7,6
kontroll jord "A"	7,2	7,8

Appendix D

Other figures not included in results.

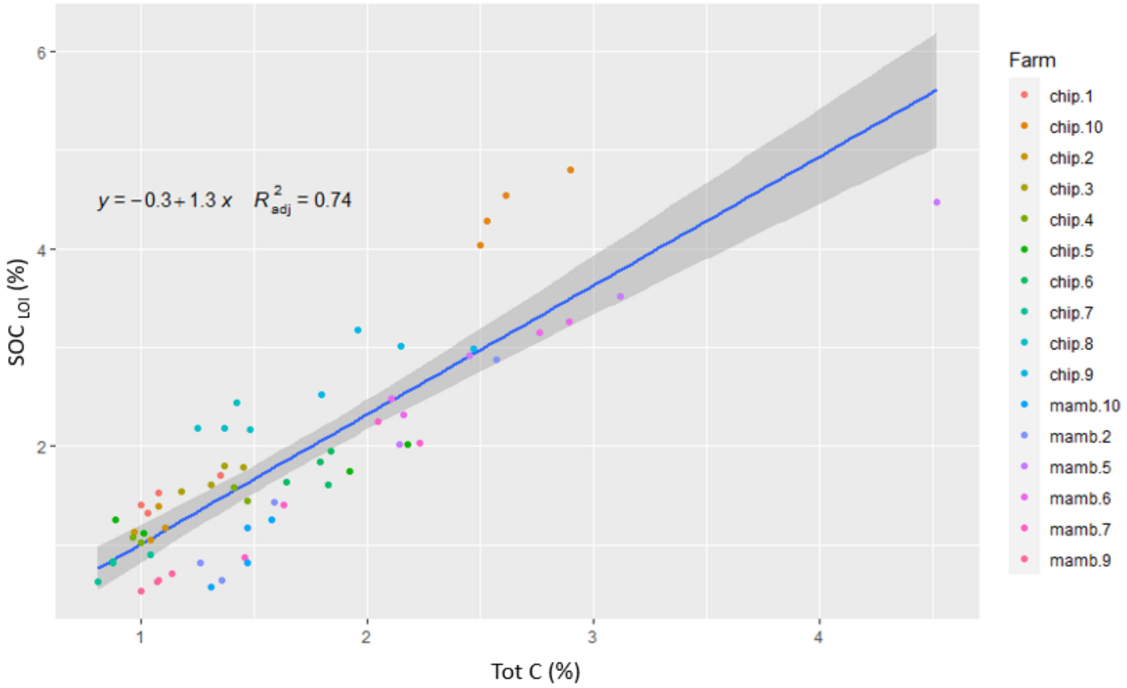

Figure: Relationship between SOC_{LOI} and $SOC_{tot\ C}$. Strongly correlated. Model explained 74%.

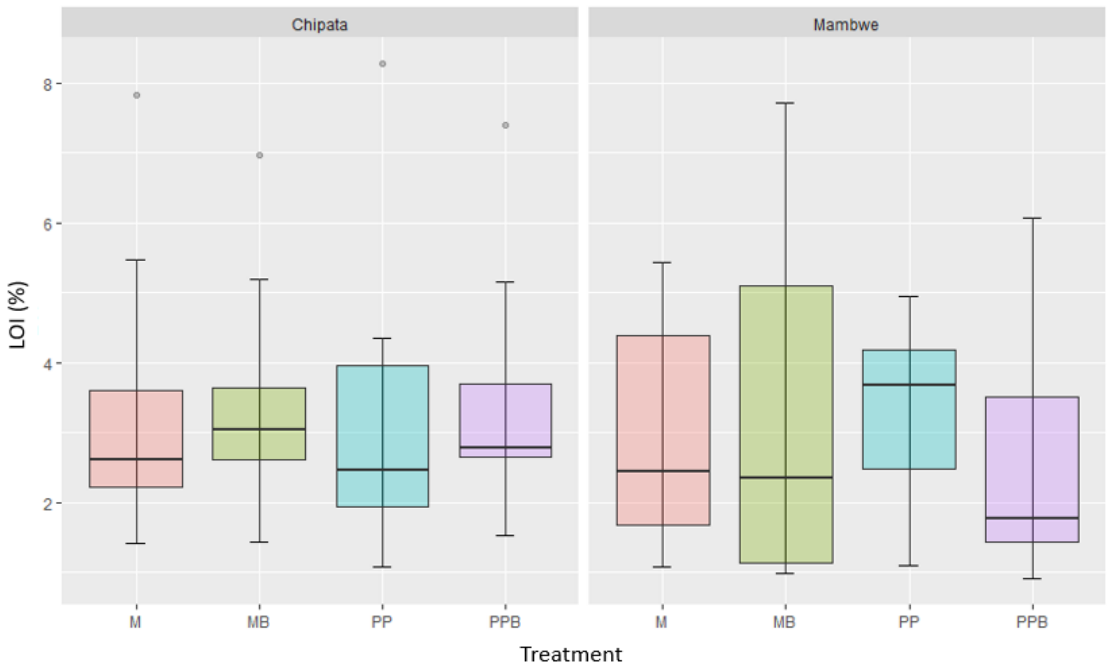

Figure: SOM in each district and for each treatment. Treatments; M = maize, MB= maize with biochar, PP= pigeon pea, PPB = pigeon pea with biochar. No significant difference between treatments (p>0.05).

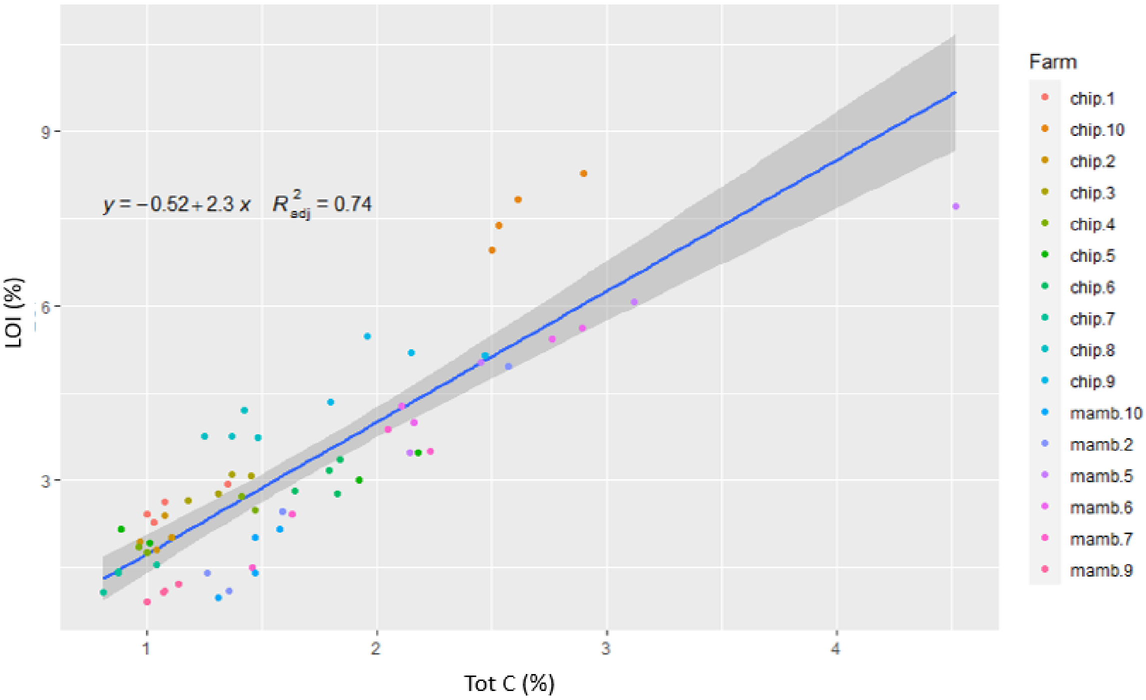

Figure: Relationship between SOM and tot C. Strongly correlated.

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