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Effects of Biochar and Crop Rotation with Maize and Pigeon Pea on soil Phosphorous Availability in Chipata and Mambwe, Zambia

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Abstract

Sub- Saharan Africa (SSA) faces significant challenges in agricultural production due to soil degradation, costly fertilizers, and reliance on precipitation. Conservation agriculture has a potential to mitigate these challenges through practices such as biochar (BC) addition and crop rotation. However, the effects of BC and crop rotation on soil phosphorus (P) availability in SSA is understudied.

This thesis will investigate the impact of BC addition and crop rotation with maize and pigeon pea (PP) on soil P availability, in the Eastern districts of Chipata and Mambwe in Zambia. Eighteen farms were selected and divided into four treatments to assess the effects on soil characteristics. Soil samples were collected and analyzed for pH, P-AL, total P, organic P, inorganic P, and oxalate extractible P, Fe and Al. The analyses showed that the soils were slightly acidic to neutral (pH = 5.39 - 7.18) and had varying P-AL concentrations (3.2 mg/kg - 480 mg/kg). Chipata exhibited higher total P, but lower P-AL compared to Mambwe, possibly attributed to differences in pH and phosphorus saturation degree (PSD).

Contrary to expectations, the study found no significant effects of BC addition or crop rotation with PP on P availability. High background levels of P-AL might have masked the potential changes. Potential removal of BC while sieving the soil samples might also have removed P from the BC samples. These findings underscore the complexity of soil nutrient dynamics in SSA and highlight the need for further research to find effective strategies for enhancing agricultural production sustainability.

Sammendrag

Afrika sør for Sahara står ovenfor en rekke utfordringer innenfor jordbruksproduksjon på grunn av nedbrutt jordsmonn, dyr kunstgjødsel og høy avhengighet av nedbør. «Conservation agriculture» kan potensielt motarbeide utfordringene gjennom tilførsel av biokull og vekselbruk. Effektene av biokull tilførsel og vekselbruk på tilgjengeligheten av fosfor er derimot lite studert.

Denne oppgaven skal undersøke påvirkning av biokull tilførsel og vekselbruk med mais og pigeon pea på tilgjengeligheten av fosfor i jorda i distriktene Chipata og Mambwe i Zambia. Atten gårder ble valgt og inndelt i fire behandlinger for å vurdere påvirkningen på jordkjemiske egenskaper. Jordprøver ble innsamlet og analysert for pH, P-AL, total P, organisk P, uorganisk P og oksalat løselig P, Al og Fe. Analysene viste at jorda var litt sur til nøytral (pH = 5.39 – 7.18), og hadde varierende mengde med tilgjengelig P (3.2 mg/kg – 480 mg/kg). Chipata hadde mer total P, men mindre plantetilgjengelig P sammenlignet med Mambwe, muligens på grunn av lavere pH og høyere fosfor saturerings grad (PSD).

I motsetning til forventninger fant forsøket ingen effekt av biokull tilførsel og vekselbruk med pigeon pea på tilgjengeligheten av fosfor. Høye bakgrunnsnivåer av tilgjengelig fosfor kan ha gjort det vanskelig å oppdage relativt små endringer. Siktingen av jorden kan også ha fjernet noe av biokullet, som kan ha fjernet fosfor fra jordprøvene med biokull. Resultatene viser kompleksiteten av tilgjengeligheten av næringsstoffer i jord i Afrika sør for Sahara. Det er et behov for videre forskning for å finne effektive strategier for å forbedre bærekraftig jordbruksproduksjons.

Acknowledgments

This thesis marks the ending of five fantastic years in Ås where I have been able to study the environment and learn about the soil on which we depend to produce food. I am grateful for the inclusiveness of all students and employees at NMBU who contributed to making these five years interesting and productive.

I would like to thank Prof. Vegard Martinsen and Prof. Jan Mulder for assisting me in my work and including me in this project. I would also like to thank the participants of the weekly meeting with PhD and MSc students studying CSA related topics, for giving good feedback and tips to this thesis, and giving me insight to their work. The team at UNZA helped a lot with organizing my stay in Zambia for the fieldwork for which I am very grateful. A special thanks to PhD student Miyanda Moombe (UNZA) and Obby Hlima (CSCF) for all the help during the fieldwork and for introducing me to the farmers who were a part of the study. I would also like to thank Irene E. Eriksen Dahl, Mona Mirgeloybayat and Valentina Zivanovic for helping me with lab analyses, and being available for questions about the methods used.

I want to thank girlfriend Vivian Y. Bolkan who always support me and brighten up my days. With you by my side I feel that everything is possible. I want to give a big thank you to my fellow students in the cellar of the soil building at NMBU. We have experienced highs and lows together, and the social aspects helped me reduce stress and kept me focused. Lastly, I want to thank my brother Torbjørn R. Fyrvik and parents Jorunn Reitan and Torkel Fyrvik who helped with proofreading towards the end and gave good suggestions.

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List of abbreviations

Al = aluminum

AL = ammonium lactate

Al_{ox} = aluminum oxide

BC = biochar

C = carbon

CA = conservation agriculture

Fe = Iron

Fe_{ox} = iron oxide

K = potassium

N = nitrogen

NMBU = Norwegian University of Life Sciences

OM = organic matter

P = phosphorus

$[PO_4]^{3-}$= phosphate

P_{ox} = phosphorus oxide

PP = pigeon pea

PSC = phosphorus sorption capacity

PSD = phosphorus sorption degree

PZS = point of zero charge

SOC = soil organic carbon

SSA = Sub- Saharan Africa

UNZA = University of Zambia

1. Introduction

1.1 Thesis outline

The thesis is divided into sections following the IMRaD methodology. Section 1 Introduction starts with detailed background on agriculture in Zambia, nutrient availability in soils, Conservation Farming (CA), phosphorous (P), pigeon pea (PP) and biochar (BC) based on a state-of-the-art literature review. Then there is a problem statement followed by research objectives and hypotheses. Section 2 Materials and Methods describes the methodology and materials used in the thesis. This includes a site description, methods for collecting soil samples, and description of the laboratory analysis used, as well as a description of the statistics used on the data. Section 3 Results presents all results, starting with underlying soil properties, then going over to pH, different P fractions in the soil, and the relationship between the different P fractions. Section 4 Discussion use the results presented in section 3 and links the results up to the hypotheses in section 1. Section 4 also compares the results found in this study to other similar studies. In section four there is also included weaknesses of this study, and future work to be done as well as a management recommendation. Lastly section 5 Conclusion consists of a summary and a conclusion.

1.2 Background

Ending world hunger is the second United Nations (UN) sustainable development goal. The goal includes improved food security, improved nutrition, and promotion of sustainable agriculture (United Nations, 2024). One area where undernourishment is a challenge is Sub-Saharan Africa (SSA), home to 1.18 billion people or 13% of the World's population (O'Neill, 2023). The population is also rising rapidly and is projected to reach 3.8 billion by 2100 (Kaneda et al., 2021). Vulnerability to climate change is a big concern for agriculture in SSA due to the dependence on precipitation for yields. Precipitation is predicted to decrease in multiple areas and become increasingly more variable in SSA (Serdeczny et al., 2017). Another challenge for agriculture in SSA is degraded land. Degraded land makes up 65% of the agricultural land in SSA. Land degradation induces declines in soil biological, chemical and physical properties, and as an effect reduce in the soil's capacity to provide ecosystem services like being a medium for crop production (Kihara et al., 2020). Therefore, there is a need to develop agricultural methods that are adapted to climate change and can prevent further land degradation.

In the SSA country of Zambia, the availability of phosphorus (P) in the soil is low and can be a limiting factor for crop production (Yerokun, 2008). To combat P limitations, mineral fertilizers can be used in the fields; however, this is not a viable option for most farmers due to the high costs of mineral fertilizers. Thus, there is a need for methods to increase available P in agricultural land in Zambia and other parts of SSA to achieve greater agricultural production. This study will focus on soil P in Zambia and evaluate possible methods for increasing P availability in Zambian agricultural soils.

1.2.1 Agriculture in Zambia

In Zambia, three-quarters of the population works in agriculture (International Trade Administration, 2022), and their livelihood depends on the yearly yields. The vast majority work on small-scale, family-owned farms and of the roughly 1.4 million smallholder households 83.3% grow maize for both subsistence and income (Mulenga et al., 2017). In addition to maize, other crops produced in Zambia include peanuts, soya, sorghum, millet and cassava (Croptrust, 2024). Dependence on precipitation is large in Zambian agriculture due to only 1% of smallholder farmers using irrigation for field crops (Ngoma et al., 2019). Due to this lack of irrigation systems on most small-scale farms, there is a strong link between precipitation and yields. There is a distinct rainy season in Zambia usually starting in November and ending in April; however, precipitation will likely decrease with climate change (Libanda & Ngonga, 2018) which may make agriculture more difficult. Zambia is divided into three agro-ecological regions where precipitation is the distinguishing factor (Figure 1). Region 1 is located mainly in the South, and it receives less than 800 mm of rainfall annually. Region 2 receives from 800 mm to 1000 mm of annual rainfall. The region stretches like a band through the country from the Western border with Angola to the eastern borders with Mozambique and Malawi. It is divided into agro-ecological regions 2a (east) and 2b (west). Region II is also the most populated. Region 3 makes up the Northern part of Zambia where it rains more than 1000 mm annually. Due to the high annual rainfall, the soils in this region are leached (Jain, 2007), which means materials are eluviated downward in the soil and plant nutrients are lost (Britannica, 2010).

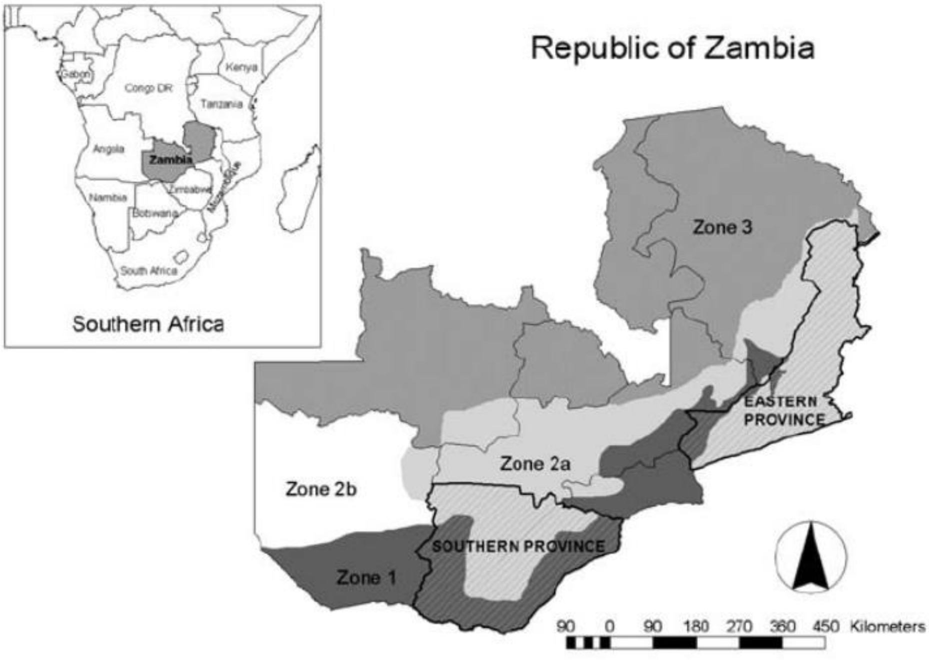


Figure 1: Map over Zambia with the different agro-ecological zones marked in gray tones. Rainfall is the main factor which determines the agro-ecological zone (Mtambo et al., 2007).

1.2.2 Conservation agriculture

Conservation agriculture (CA) is an agricultural method that includes minimal soil disturbance, crop rotation and a permanent soil cover (Gonzalez-Sanchez et al., 2015). The method has been promoted by stakeholders in the Zambian agriculture sector, both from the government and from the private sector (Haggblade & Tambo, 2003). This has led to a 5% adoption rate of CA for households in Zambia in 2008 (Arslan et al., 2014).

An important effect of CA is carbon sequestration which can mitigate climate change (Powlson et al., 2016). This can be attributed to how CA contributes with organic matter to the soil from the retention of crop residue. Especially the top 5 cm of the soil column is affected, while the influence decreases with soil depth (Zhang et al., 2016). As a result of the CA in Zambia soil organic carbon (SOC) increased by 0.05 tons/ha/year in the top 20 cm of the soil column (Martinsen et al., 2019). The sequestration ability of CA is however still under debate with multiple studies not recording an increase in SOC with the use of CA (Corbeels et al., 2015; Giller et al., 2015).

Furthermore, CA can contribute to higher yields. In a study by Corbeels et al. (2020), the use of CA showed increases in the yield of maize by 8.4% in SSA and Mulder et al., (2016) found an increase as high as 30%. This can partly be attributed to CA basins and riplines that improve water infiltration, water retention and plant root development (Haggblade & Tambo, 2003). However, the yield effects of CA vary and there is still a need for more information (Corbeels et al., 2020). Intercropping with legumes also plays a vital role in increasing maize yields. Following intercropping with legumes maize yields increased greatly, up to double compared to continuous maize under no-till (Cairns et al., 2015). This is due to the N-fixating properties of legumes as well as increased resilience from plant deceases due to plant diversification (Cairns et al., 2015).

1.2.3 Nutrient Availability

Plant growth can be limited by many biophysical factors such as water availability, temperature, light, and nutrient availability (Vedagiri & Smith, n.d). Nutrient availability is limited to the mineral and organic fertilizers added by humans and the natural mineralization of organic matter (OM) in soils. However, most nutrients change form depending on pH and therefore pH can as well affect the availability of nutrients. Figure 2 shows how a majority of nutrients are most available in a neutral or slightly acidic soil (Roques et al., 2013)

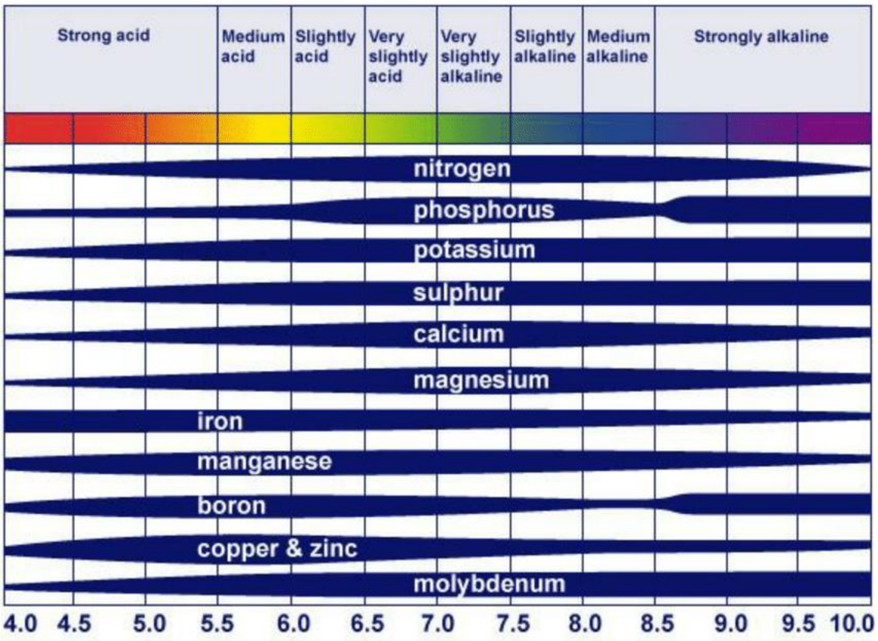


Figure 2: Changes in availability of soil nutrients dependent on soil pH. Thicker lines indicate higher availability (Roques et al., 2013).

In Zambia, the price for 50 kg of mineral fertilizers is 500-1300 ZMW kwacha (19-50 USD) (eMiska, 2024) which many smallholder farmers cannot afford with the median yearly salary for farmers in Zambia being 19 380 ZMW (730 USD) (World Salaries, 2024). Therefore, most smallholder farmers are limited to the nutrients mineralized in the soil from OM during the growing season. The outputs of nutrients from soils consist of plant uptake and subsequent crop harvest and residues, leaching, denitrification and erosion (Færge & Magid, 2004).

For the three main nutrients; phosphorous (P), nitrogen (N) and potassium (K), the outputs are higher than the inputs in SSA making the nutrient balance negative, with harvest of crops and erosion being the strongest negative contributors (Smaling et al., 1993). Leaching also plays a crucial role for N and K, while P is less susceptible because of its lower mobility in the soil (Cobo et al., 2010). The P is easily stabilized in resistant forms in the soil which makes the P unavailable for plants, due to sorption to Al and Fe oxides (Yerokun, 2008). This immobilization of P is dependent on pH which affects the charge on variable charged minerals like Fe and Al oxides. These minerals have a point of zero charge (PZC) at one specific pH, and if the pH decreases from PZC the surface becomes positively charged leading to increased P sorption (Penn & Camberato, 2019).

1.2.4 Phosphorus

P is a macronutrient and makes up about 0.2% of a plant's dry weight (Schachtman et al., 1998) and is important for many processes and formations in organisms. For example P is an important structural compound of DNA and RNA (Walsh, 2021). Adenosine triphosphate (ATP) is the energy source of cellular function, and a key component of the molecule is P. Furthermore P is involved in water transport and photosynthesis in plants (Belvins, 1999).

Plants get their P from the soil through roots and mycorrhiza. At low P availability, mycorrhizal uptake makes up a large part of the total P uptake, but in severely P-impoverished habitats the mycorrhizal strategies are less effective than other P-mobilizing strategies (Lambers, 2022).

In soil, P can take different forms. In the solid phase of soil, the bulk P is considered to be (1) adsorbed to the surface of soil particles, (2) sparingly soluble minerals, and (3) organic compounds, while some P is also in the lattice of clay and other silicate minerals (Larsen, 1967). Of these forms, the inorganic phosphorous that are most available for plant uptake is phosphate ($[PO_4]^{3-}$) (Schachtman et al., 1998). Which form of $[PO_4]^{3-}$ is in the soil is determined by the pH. In extremely acidic conditions (pH < 2.12) the main form of $[PO_4]^{3-}$is H_3PO_4, and in less extreme acidic conditions (pH = 2.12 – 7.2) the main species of PO_4 is $H_2PO_4^-$, while in alkaline conditions (pH = 7.2 – 12.36) HPO_4^{2-} is the dominating species (Chen et al., 2021). In even more alkaline conditions (pH > 12.36) the dominating P species is $[PO_4]^{3-}$ which is unavailable for plants to use (Figure 3).

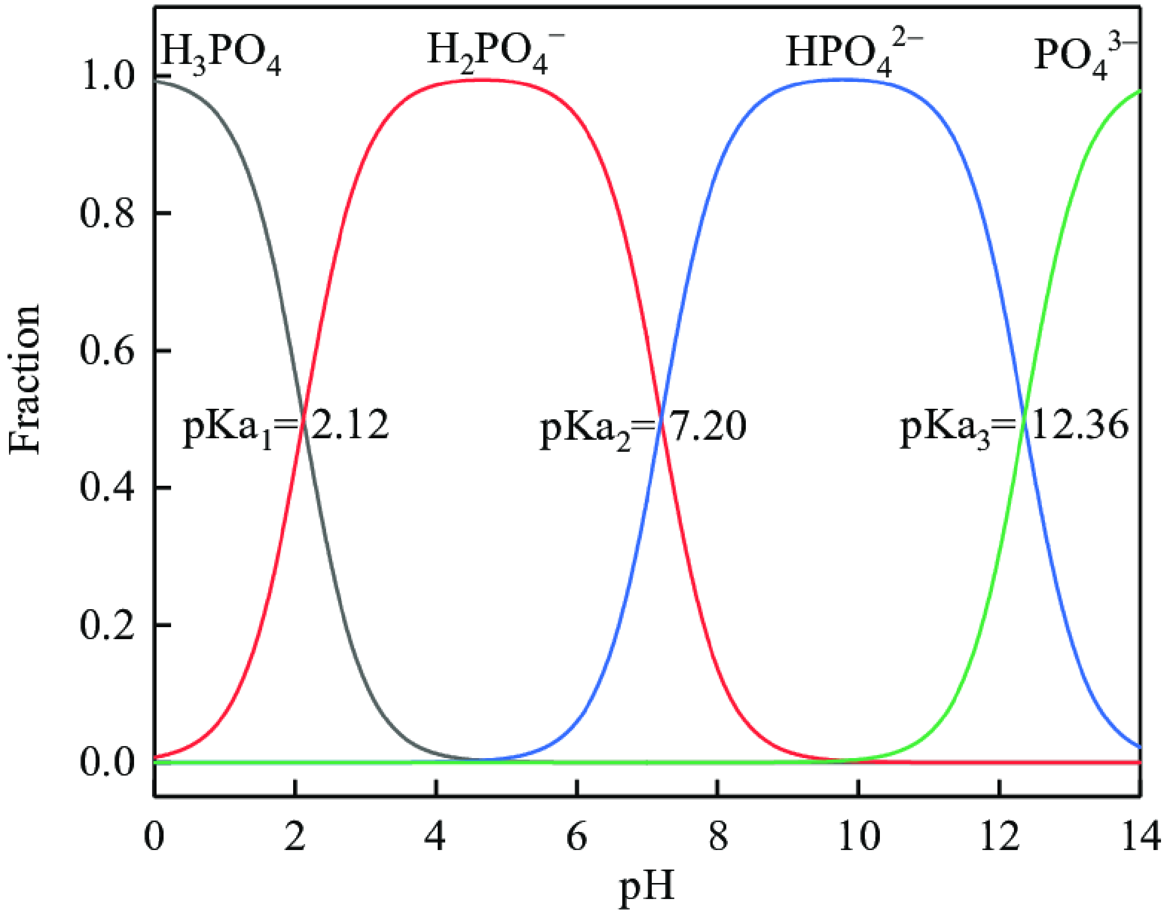


Figure 3: Different species of $[PO_4]^{3-}$ in soils as effect of pH. At low pH, $[PO_4]^{3-}$ is mostly H_3PO_4 and with increasing pH, H^+ leaves the $[PO_4]^{3-}$until only PO_4^{3-} is left at very high pH (Chen et.al 2021).

The fraction of P found in the organic material has to be converted into inorganic compounds before it is available for plant uptake through mineralization by microorganisms found in soil (Prasad & Chakraborty, 2019). The rate of the mineralization of P is affected by physical soil properties like pH, moisture and texture, biological soil properties like phosphatase activity and respiration rate, and chemical soil properties like different fractions of P in the soil, total N and total C content (Harrison, 1982). The composition of the organic material also plays an important role in the fate of P, especially the C:P ratio. With a C:P ratio of 200:1, the P is mainly mineralized and with a ratio of 300:1, the P is mainly immobilized in microbial biomass (Arenberg & Arai, 2019). The soil pH can explain 11.2% of the total variation in Po-mineralizing-related gene abundance (Wan et al., 2021) which indicates that mineralization is partly controlled by soil pH.

1.2.5 Pigeon pea

Pigeon pea (PP, *Cajanus Cajan*) is a legume used as a food crop in the tropics and subtropics, and makes up 5% of the total legume production in the World (Hillocks et al., 2000). Most of the production of PP is in India, but other countries like Kenya, Tanzania, Malawi, Uganda, Nepal and Myanmar also cultivate PP (Singh & Jauhar, 2005). PP can be used effectively in helping rehabilitate degraded land and depleted soil, partly due to its high N-fixating capacity (Abebe et al., 2016). A study by Myaka et al. (2006) showed that up to 60 kg of N per ha was added to the soil after the cultivation of PP, only 25% of which was exported in the grain (Myaka et al., 2006). Furthermore, the deep roots of PP can access nutrients and water deeper down in the soil compared to other crops like maize (Odeny, 2007). The roots of PP also release effective root exudates for releasing Fe-bound P in the soil (Ae et al., 1990). However, Myaka et al., (2006) did not find that PP mobilized large amounts of sparingly soluble P into organic forms, but they showed an accumulation of up to 6 kg of P per ha to the soil where only 25% was exported in the grain. In the long run, this can lead to increased soil fertility. However, studies have shown that use of PP in Zambia has not resulted in an increase in P availability in the soil; indeed, a decrease was observed in one of the regions (Phiri et al., 2024). Still, Renwick et al., (2020) showed that there is potential for intercropping PP with maize and in Eastern Africa to an increase both soil P pool and in yield per area compared to maize monoculture, especially under dry conditions. The effects of PP on soil P are still not fully understood and need to be researched further. This thesis aims to contribute to this effort.

1.2.6 Biochar

Biochar (BC) is a carbon-rich material made from the pyrolysis of biomass, often waste products from agriculture like plant residue. BC can act as a carbon (C) storage once added to the soil due to its stability and long decomposition rate (Xie et al., 2016). This leads to a long residence time of BC in soil and BC therefore slows down the C-cycle (Lal, 2016). This can offset some of the C released into the atmosphere by human activities. The addition of BC to the soil can also improve soil properties making it better for crop production. Cation exchange capacity (CEC) increases in soils where BC is added; BC thus helps with the retention of nutrients in the soil (H. Singh et al., 2022). Moreover, the chemical forms of P in the soil can be altered when BC is added, but the effects are variable and depend on the properties of the soil and BC used (Ghodszad et al., 2021). The microbial mineralization of P also increases with the addition of BC under low inputs of P (Tian et al., 2021). Furthermore, applications of BC may also increase the pH in the soil (Gondek et al., 2018) which alters the chemical properties of P in the soil. At low pH OH^- sorbed to Fe and Al oxides will accept protons and free coordination positions since H_2O is an easier ligand to displace than OH^-. This facilitates ligand exchange with anions like $[PO_4]^{3-}$. P bound to Fe and Al oxides has a much lower desorption rate than adsorption rate, and sorbed P to Al and Fe oxides is therefore locked away and unavailable for plants. An increase in pH will work against this ligand exchange process, and less P will be sorbed to Fa and Al oxides, thereby leaving more P available for plants in the soil (McBride, 1994). Furthermore addition of BC increases soil organic carbon (SOC) and subsequently the SOC / Fe and Al oxides ratio, which partly determines the P availability (Hawkins et al., 2022). Other nutrients are also affected by the addition of BC, for example, BC from PP increases levels of NO_3^- in the soil (Munera-Echeverri et al., 2022).

1.3 Problem statement

P has many forms in soil and can be divided into organic and inorganic forms. Inorganic P includes $[PO_4]^{3-}$ions in solution, $[PO_4]^{3-}$sorbed to positively charged minerals like Al and Fe oxides and clay mineral surfaces, and occulated P captured in crystalline Fa and Al oxides. The organic fraction consists of the P found in plant residue, as well as P in soil organisms. All these forms can potentially be altered with the addition of BC, partly due to increases in pH which will decrease the potential for sorption of P to Al and Fe oxides. Change in pH can also alter the mineralization rate of P found in plant residue. Furthermore, the BC contains organic P which will change the C:P ratio in the organic soil fraction. Since the C:P ratio can alter the fate of P in soil the change would impact the P cycling in the soil.

The crop rotation with maize and PP will also influence the soil P. PP can access deeper in the soil column as well as use P unavailable for other plants. This increased uptake could decrease the soil P pool in the short term, but in combination with CA which includes retention of plant residue, this could increase P availability further up in the soil column.

There is a lack of data on how BC in combination with crop rotation will affect plant available P in the soil in field conditions in SSA. This thesis aims to assess the effects of BC and crop rotation on soil phosphorous in Zambia by looking at plant available P, total P, inorganic and organic P as well as oxalate extractible P.

1.4 Research objective and hypotheses

1.4.1 Objectives

The main objective is to evaluate the effect of BC on P in soils under crop rotation with maize and PP. This led to the three research objectives:

1. Evaluate the effect of BC on P availability in the soil.
2. Evaluate the effect of crop rotation on P availability in the soil.

1.4.2 Hypotheses

To complete the objectives the following hypothesis were selected and tested:

1. BC will increase the plant available P in the soil.
2. Crop rotation with PP will increase plant available P in the soil.

2. Materials and methods

This section outlines the methods used in the present work. This includes a description of the site and species of the case study, as well as details about the methodology for collecting and analyzing data.

2.1 Site description

The study area consists of 18 farms in Zambia's Eastern province (Figure 4). Ten of the farms are in the Chipata district (Figure 5) and the other eight are found in the Mambwe district (Figure 6). The farms are referred to as CHIP 1 – CHIP 10 for the ten farms in Chipata, and MAMB 2 and MAMB 4 – MAMB 10 in Mambwe. All these farms are part of an ongoing research project that is a collaboration between the Norwegian University of Life Sciences (NMBU) and the University of Zambia (UNZA). The study sites in Chipata are in agro-ecological zone 2a, while the study sites in Mambwe are in agro-ecological zone 1 (Figure 1). Appendix A gives the coordinates of all the farms. Originally, ten farms in each district were a part of the project, but two of the farms in Mambwe left, which is why the district is represented by only 8 farms.

Figure 4: The location of Zambia in Africa highlighted in red (insert) and the farms' locations within Zambia; purple pins indicate farms in Chipata and orange pins farms in Mambwe. Map made using Google Earth on 18th of March 2024.

Figure 5: Locations of all ten farms in Chipata. The map was made in the software QGIS Desktop 3.22.4 18th of March 2024.

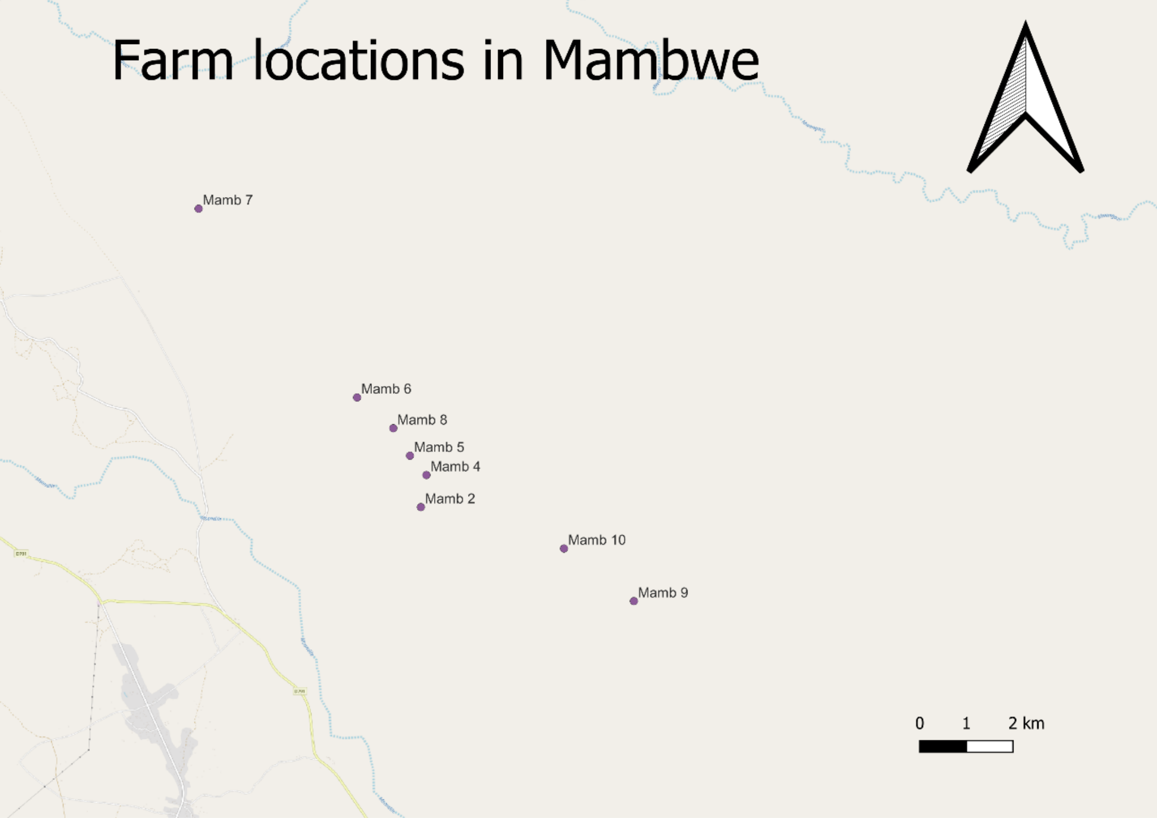


Figure 6: Locations of all eight farms in Mambwe. The map was made in the software QGIS Desktop 3.22.4 18th of March 2024.

2.2 Study layout

At each of the farms, an area of 2500 m^2 (one lima) was divided into four quadrants of 25m x 25m (Figure 7). Two of these four quadrants received BC (pair 1) while the other two did not (pair 2). The added BC was made from maize cob and amounted to 250 kg per quadrant, equivalent to 4 tons per ha. Each quadrant pair (with/without BC) had one quadrant with maize and one with PP in the first year. The four treatments on each farm will be referred to by the abbreviations: M (maize without BC), MBC (maize with BC), PP (Pigeon pea without BC) and PPBC (Pigeon pea with BC). The two study species in this study include the previous mentioned PP (*Cajanus Cajan*) and the stable crop of Zambia maize (*Zea mays L.).* On both quadrants of each farm with maize, fertilizers were added at a ratio of 200 kg/ha for compound D, and 200 kg/ha for Urea. The next year the crop in each quadrant changed to create a crop rotation effect. The plots had been in production for one year before the fieldwork for this thesis was conducted.

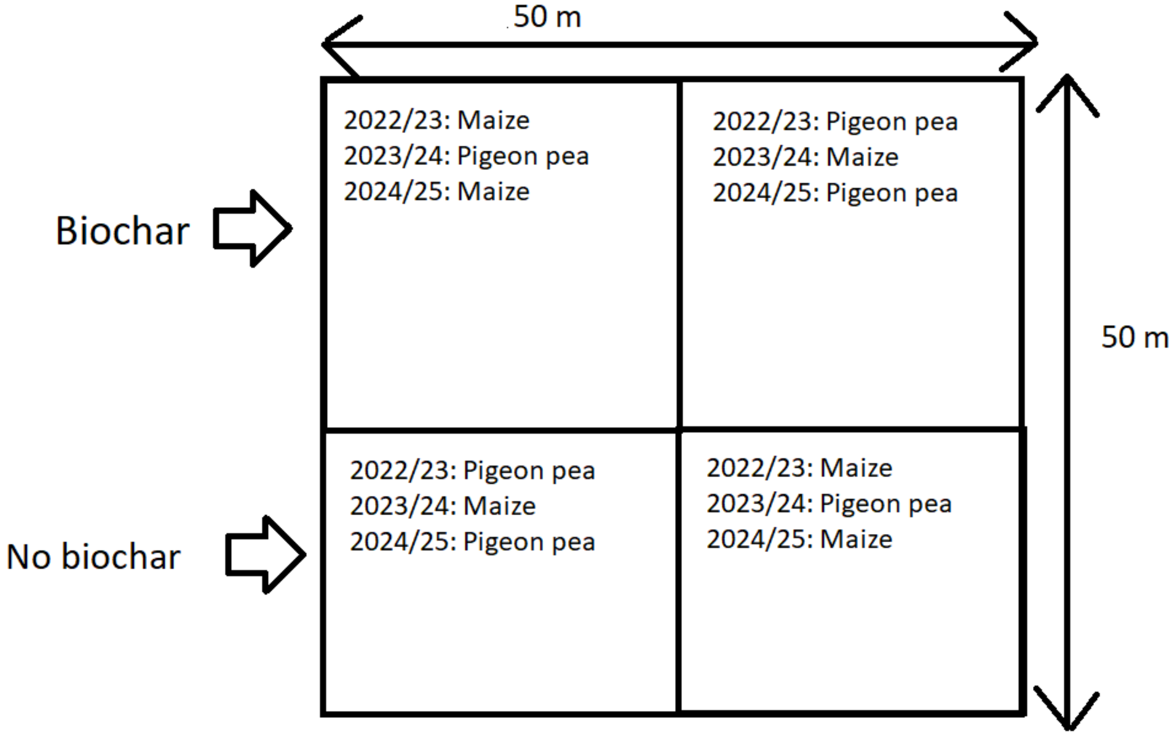


Figure 7: Each of the farms was divided into four quadrants where BC was added to two quadrants. Each year the crop in each quadrant alternated between maize and PP. The total width and length of the field were 50 m, and each plot had a length and width of 25m.

In addition to the two farms in Mambwe that left the project, two of the remaining eight farms in Mambwe decided to grow sunflowers on one of their plots. Thus, only maize plots with and without BC are considered for these two farms. Furthermore, one farm in Chipata (CHIP 6) had BC on both PP quadrants and no quadrant with PP and no BC.

From each plot, soil samples from eight subsamples were collected (0-20 cm), mixed and joined to one sample for each plot for a total of 68 soil samples (n = 18 for M and MBC plots, n = 17 for PPBC and n = 15 for PP). For some farms where the amount of BC did not cover the whole BC plot, subsamples were only collected where BC was visible.

The farmers had the responsibility of applying BC to the fields. To ensure cohesiveness all farmers were invited to a BC making practice organized by Climate Smart Farming Solutions (CSFS). BC was made in a hole in the ground (depth = ca. 2m, radius = ca, 1.5m) where a small fire was started at the bottom. Maize cobs were gradually added to the fire so only the top layer burned (Figure 8). If the fire produced smoke, addition of maize cobs is to fast. If the top maize cobs in the fire turned to ash, addition of maize cobs is to slow. After the hole was almost filled water was used to put out the fire. Then banana leaves were put on top and with a soil layer covering the pit. Water was then sprayed on top of the soil, filling the pores with water, and limiting oxygen access. After a couple of days, the cover was removed and the BC was done. The BC was added to the soil by the farmers before the growing season in either riplines or basins which were dug by hand at 20 cm belove the soil surface.

Figure 8: Production of BC on training organized by CSFS.

2.3 Data and data collection

The following section will describe the soil sampling method and a detailed description of the laboratory analyses of pH, P-AL, total P, organic P, inorganic P, Al, Fe and P oxides. The statistical analyses of the data will then be presented.

Field work was conducted in collaboration with Kjersti Bach Moholt, another master student at NMBU. Some of the analytical results from the same samples as well as site description and experimental setup are reported in her masters' thesis "The effects of pigeon pea and biochar on soil nitrogen and carbon in Chipata and Mambwe, Zambia".

2.3.1 Soil samples

From each plot, eight sub-samples from the top 20 cm of the soil were bulked to make up one composite soil sample. The resulting composite samples were sieved through 2 mm mesh in the field of which 0.5 kg were put in plastic bags for transport to UNZA in Lusaka, Zambia and then to NMBU in Ås, Norway. One 200-g sample from each plot was brought to NMBU for laboratory analysis. In total 68 samples were collected. A team at the UNZA collected bulked soil samples from each plot during August 2022 right before the BC project started. These samples were used to measure among other things pH, soil texture and Bray-P which will be used as background data in this study. Before the project started most of the farms cultivated maize, but some had cotton, groundnuts and soybeans.

2.3.2 Laboratory analysis

The following laboratory analyses were all done in the soil laboratory located at NMBU. The analyses were done with great help from the laboratory technicians employed in the laboratory.

2.3.2.1 pH

Acidity, usually measured by the potential of Hydrogen, or pH, is often used as a parameter in soil science because it influences most chemical processes in the soil. The standard method for measuring pH at NMBU, outlined in Krogstad & Børresen, (2015) was used in this study. 10 ml of soil was added to plastic beakers with lids, and 25 ml of distilled water was added to each beaker. The breakers were then shaken by hand before they were left overnight. The morning after the beakers were shaken by hand again. Repeated shaking is important to release all H^+ from the soil. After 15 minutes, when the soil had sedimented to the bottom of the breakers, the pH was measured with a PHM210-type pH meter. The pH meter was calibrated with solutions of pH 7 and 4 and tested for a control solution with a pH of 6.87. The pH meter was in the solution for less than 2 minutes and never touched the sediment in the bottom of the breakers. Between each measurement, the pH meter was cleaned with distilled water and dried with paper tissue. The same method was used to measure pH_{CaCl2}, but this time 0.01 M $CaCl_2$ was used instead of distilled water.

2.3.2.3 Total, inorganic and organic P

Total P and inorganic P were measured following the method proposed by Møberg & Petersen, (1982). Soil was added to clean glass bottles for inorganic P and in crucibles for total P, with 1.00 g of soil in each bottle/crucible. The crucibles were placed in a furnace at 550°C for 1 hour, burning the organic material in the soil and consequently converting organic P to inorganic P in the ash fraction. After burning, the samples were cooled, and the content was transferred quantitatively from the crucibles to glass bottles. 5 ml of 6M H_2SO_4 was then added to each glass bottle for both total P and inorganic P (Figure 9). The glass bottles were placed into a water bath holding a constant temperature of 70°C for 10 minutes and then cooled for 1 hour. When the samples had cooled, they were transferred to 250 ml measuring flasks through a plastic funnel (Figure 9). Distilled water was used to clean out the remaining soil from the glass bottles and funnels into the measuring flasks. The measuring bottles were then filled to 250 ml with distilled water (Figure 10). Total P and inorganic P were then determined spectrophotometrically using the molybdenum-blue method (Shimadzu) at a wavelength of 800 nm. Organic P was then calculated by the difference between total and inorganic P using the formula (I):

I. $$Organic\ P\ \left(\frac{mg}{kg}\right) = Total\ P\ \left(\frac{mg}{kg}\right) - Inorganic\ P\ \left(\frac{mg}{kg}\right)$$

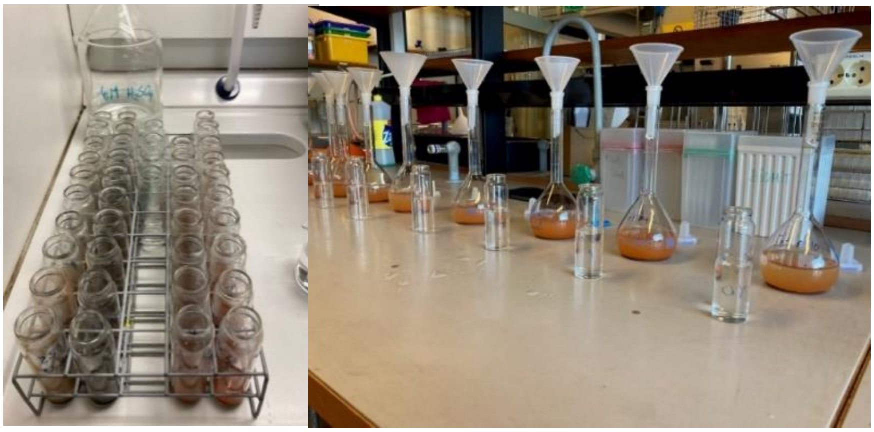


Figure 9: Picture on the left of glass bottles with 1.00 g of soil and 10 ml 6M H_2SO_4,. The soil solution was washed down plastic funnels to measuring bottles with distilled water ensuring that all soil particles were added to the measuring bottles.

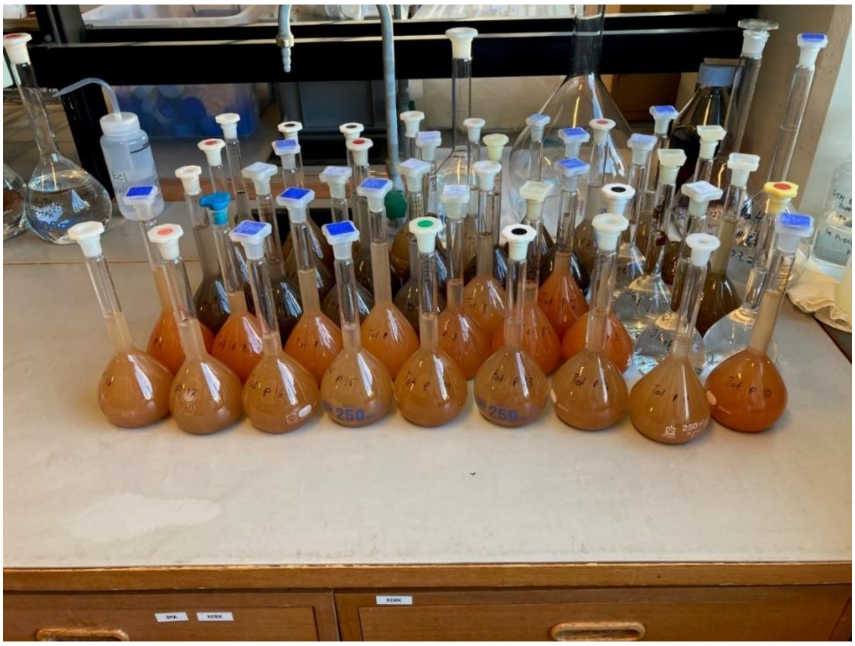


Figure 10: The samples in measuring bottles (250 ml) ready for spectrophotometry. The orange solutions in front are burned samples for inorganic P and the darker solutions in the back are unburned for total P.

2.3.2.2 Available P (P-AL)

There are several methods for measuring plant available P. The P-AL method is the standard method at NMBU and was used in the study(Krogstad & Børresen, 2015). This method is developed to mimic how plant root exudates release PO_4^- from the soil, thereby finding the P availability for plants in field conditions. The lactate in the AL solution exchanges places with $[PO_4]^{3-}$ sorbed to the cations which are released in the solution. A low pH (3.75) in the AL solution also enhances the dissolution of AL and Fe oxides, which are sorbents for PO_4.

To measure P-AL, 2.00 g of soil and 40 ml of AL solution were added to 100 ml glass bottles with lids that had been cleaned with acid. The containers were immediately placed on a shaker with 100 oscillations per minute for a total of 90 minutes at room temperature. In addition to the 68 test samples, three blanks with no soil and three control soil samples from the NMBU laboratory with known P-AL amounts were included. Blue ribbon filters (Whatman) were washed with ten times diluted AL solution and placed in plastic funnels over plastic breakers. After shaking, the samples were filtered through these paper filters and into plastic breakers (Figure 11). PO_4^- concentrations were then measured in the filtered solutions using ICP.

Figure 11: Paper filters in plastic funnels over plastic beakers to filter out soil particles.

2.3.2.4 Oxalate extractable Fa, Al and P

To measure oxalate extractable Fe, Al and P 1.00g of soil was added to 100ml glass bottles with 50m of extraction solution. The extraction solution is called Tamms solution and has a pH of 3.00 - 3.2. For each farm only one sample were tested. The quadrants with treatment = maize and no BC was selected. In total 18 samples were teste plus 4 blank samples and two samples from control soil A and two samples from control soil B which are internal control soils in the NMBU soil laboratory. The glass bottles were shaken for 4 hours in the dark before they were filtered through blue bond filters (Whatman). ICP was used to measure amounts of Al, Fa and P in the filtered samples. Phosphorus sorption capacity (PSC) and phosphorus sorption degree (PSD) were then calculated using the formulas (II - III) according to Breeuwsma & Silva, (2015):

II. $$PSC\left(\frac{mmol}{kg}\right) = 0.5 * \left[Alox\left(\frac{mmol}{kg}\right) + Feox\left(\frac{mmol}{kg}\right)\right]$$

III. $$PSD\ (\%) = \left[Pox\frac{\frac{mmol}{kg}}{PSC}\right] * 100$$

where Al_{ox}, Fe_{ox} and P_{ox} are oxalate extractable Al, Fe and P.

2.3.3 Statistical analysis

All statistical analyses were done in the statistical programming software R, version 4.3.3. The statistical analyses used were mixed effect models with the farm as a random effect. Emmeans were used to test for differences between treatments, and linear regression (lm) was used also used. Model assumptions were checked. For plotting data in bow-whiskers plots and scatter plots the package ggplot2 was used. In this study all results with $p < 0.05$ is considered significant.

3. Results

This section presents the results from the analyses outlined in Section 2 Materials and Methods. Specifically, results are presented for the soil samples' texture from the background data, bulk density, pH, P distribution, total, inorganic, and organic P, Al-extractable P, oxalate-extractable Fe, Al and P, C:P ratio and PSD.

3.1 Soil properties

The soil texture varied between the districts and the different farms in each district. The soil at most of the farms can be described as sandy clay loam. Some of the farms contained more clay and less sand and were therefore clay loam or clay. One farm in Chipata fell into the silty clay loam fraction (Figure 12). On average both districts had soils with approximately 50% sand, 20% silt and 30 % clay. However, the Chipata district had a slightly higher sand percentage and lower silt and clay compared to Mambwe (Appendix B). The bulk density of the soil was 1.34 g/cm3 in Chipata and 1.27 g/cm3 in Mambwe.

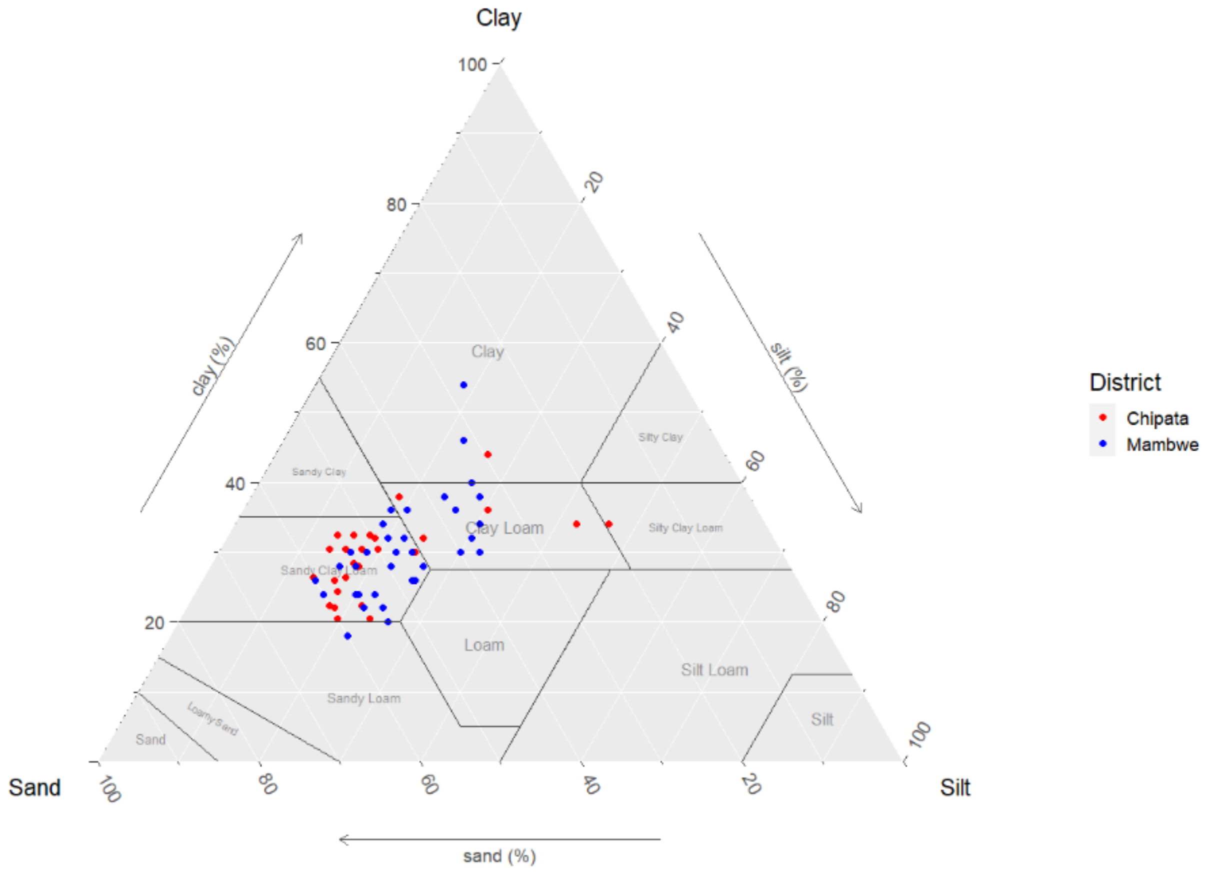


Figure 12: Soil classification of different farms where each point represents one farm. Farms in Chipata are in red and farms in Mambwe are in blue.

3.2 pH

The soil pH_{H2O} ranged from 5.39 to 7.18 in distilled water with a mean of 6.32 while pH_{CaCl2} solution was slightly lower and ranged from 4.58 to 6.73 with a mean value of 5.53. The two values are significantly ($p < 0.05$) correlated (Figure 13); thus, only pH values in distilled water (pH_{H2O}) will be reported in the following discussion.

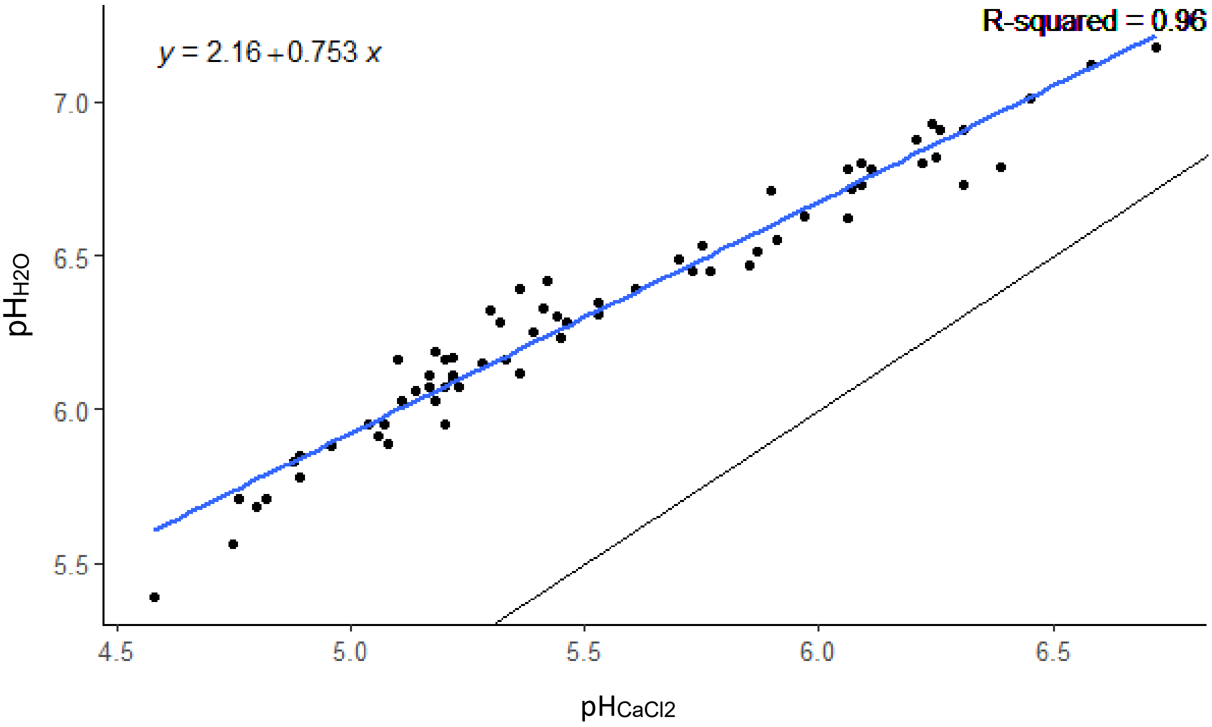
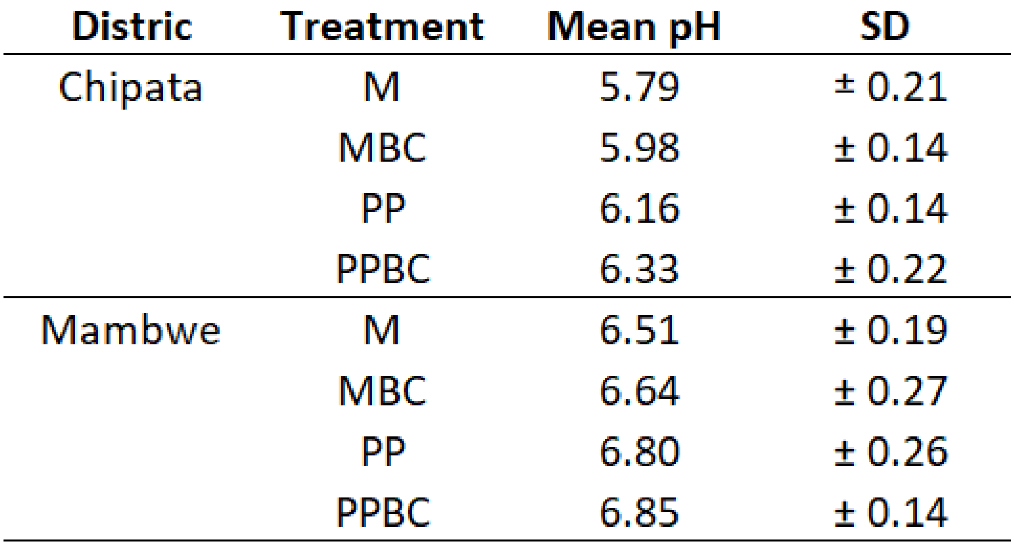


Figure 13: pH_{H2O} values plotted on the x-axis with pH_{CaCl2} values on the y-axis with a linear regression model giving the blue line: y = 2.16 + 0.753x and an R-squared value of 0.96. The black line is a 1:1 line.

The pH_{H2O} in soil samples from different treatments differed in both regions, summarized and illustrated in Table 1 and Figure 14. In Chipata, the mean pH of both quadrants with BC ($PPBC_{mean, C}$ = 6.33 and $MBC_{mean, C}$ = 5.98) was higher than the quadrants with no BC ($PP_{mean, C}$ = 6.16 and $M_{mean, C}$ = 5.79). While this trend is also observed in the pH measurements from Mambwe, the difference is smaller ($PPBC_{mean, M}$ = 6.85, $PP_{mean, M}$ = 6.80, $MBC_{mean, M}$ = 6.64 and $M_{mean, M}$ = 6.51). Furthermore, the PP plots both with and without BC were higher than Maize plots in both regions. In Chipata, the PP and PPBC had a mean pH of 6.16 and 6.33, respectively, while MBC and M had a mean pH of 5.94 and 5.79, respectively. In Mambwe, the PP and PPBC had a mean pH of 6.80 and 6.85, respectively, while M and MBC had a mean pH of 6.51 and 6.64, respectively. There are two outliers in Chipata: one with a very low pH value in the PP-plot without BC (CHIP 3) and one high value in the PP-plot with BC (CHIP 6, where both PP plots had BC) (Figure 14). There were also outliers in Mambwe with one pH value on farm MAMB 9 being very high. For the PP-plots with no BC there is one very low value from farm MAMB 2 and in the PP-plot with BC, there was one high value from farm MAMB 6.

A Tuckey test was conducted to determine which treatments in both regions differed significantly from the others with $p < 0.05$ (Figure 14). The treatments in both districts were divided into groups where each group differed significantly from the others. In group *a* both M and MBC treatment In Chipata was placed, in group *b* both PP and PPBC in Chipata, group *c* contained PPBC in Chipata and M in Mambwe, group *d* contained M and MBC in Mambwe and the last group *e* had PP and PPBC in Mambwe.

Table 1: Mean and standard deviation for pH_{H2O} *for each treatment in Chipata and Mambwe.*



Distric	Treatment	Mean pH	SD
Chipata	M	5.79	± 0.21
	MBC	5.98	± 0.14
	PP	6.16	± 0.14
	PPBC	6.33	± 0.22
Mambwe	M	6.51	± 0.19
	MBC	6.64	± 0.27
	PP	6.80	± 0.26
	PPBC	6.85	± 0.14

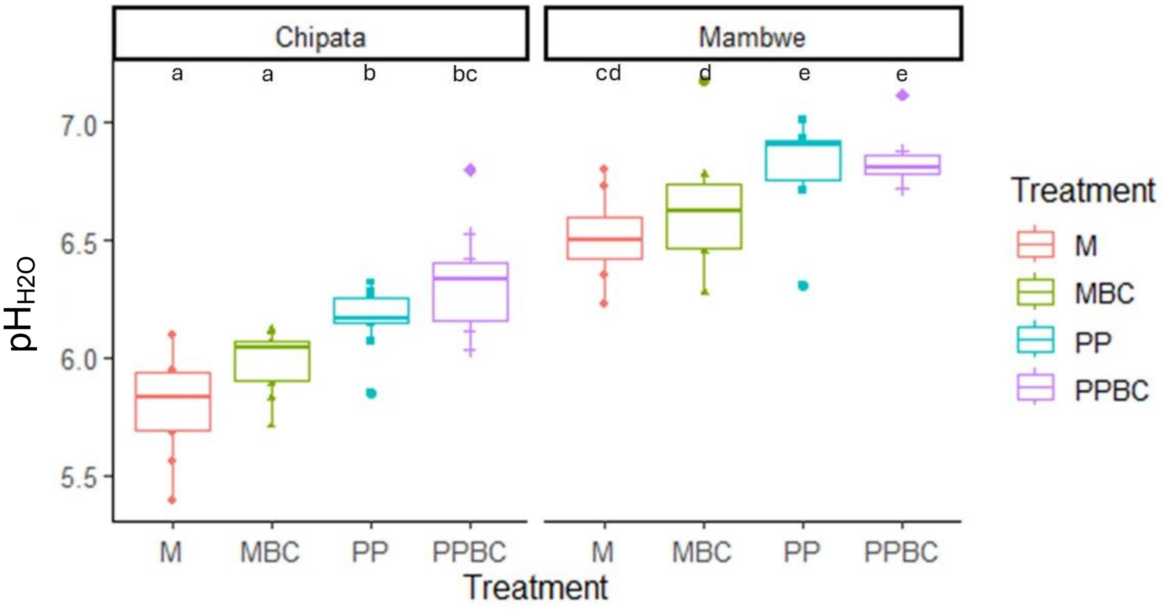


Figure 14: Box-whiskers plots of pH for different treatments for both Chipata and Mambwe. M is maize with no BC, PP is PP with no BC, MBC is maize with BC and PPBC is PP with BC. Different lower-case letters above the boxplots (a - e) indicate a significant difference ($p < 0.05$).

3.3 P distribution

Figure 15 shows the distribution of total, inorganic, organic and P-AL on all farms in mg/kg. There are large variations between the farms. There is generally more total P in the farms in Chipata than in Mambwe but two farms in Chipata (CHIP 2 & 10) have less total P than the lowest total P in Mambwe. The variation in total P is larger between the farms in Chipata compared to Mambwe.

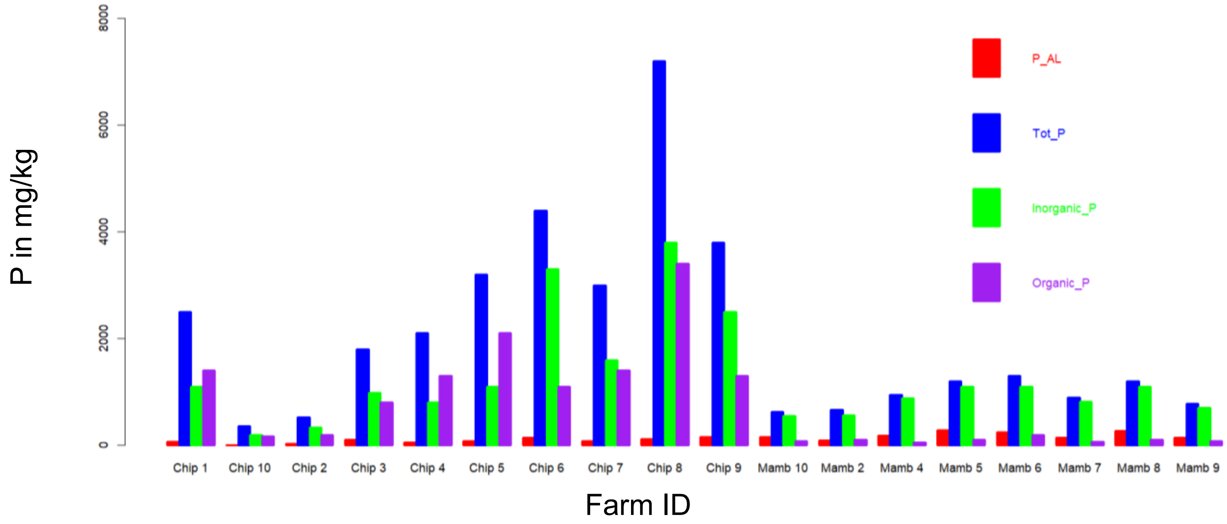


Figure 15: Averages in mg/kg of P-AL for all plots on each farm, as well as total, inorganic and organic P values in mg/kg for the plot with maize and no BC on each farm.

3.4 Total, inorganic, and organic P

Moving from the distribution across all farms to looking at general trends in each region, Table 2 presents the mean and standard deviation of total, inorganic and organic P for Chipata and Mambwe. The mean total P in the soil in Chipata was approximately three times higher (2889 mg/kg) than in Mambwe (952 mg/kg), while Chipata's variation (± 1992 mg/kg) was almost 8 times the variation in Mambwe (± 257 mg/kg). The inorganic fraction is twice as high in Chipata (1571 mg/kg) than in Mambwe (853 mg/kg), while the organic P fraction in Chipata (1318 mg/kg) is more than an order of magnitude larger than the organic fraction in Mambwe (99 mg/kg) (Table 2).

Table 2: Regional means of total, inorganic and organic P for farms in Chipata and Mambwe, with all values given in mg/kg.

District	**Mean total P** mg/kg	**SD** mg/kg	**Mean inroganic P** mg/kg	**SD** mg/kg	**Mean organic P** mg/kg	**SD** mg/kg
Chipata	2889	± 1992	1571	± 1231	1318	± 933
Mambwe	952	± 257	853	± 233	99	± 44

Inorganic and organic P make up different fractions of the total P depending on the district. In Chipata, 55% of the total P is inorganic and 45% is organic, while in Mambwe the inorganic fraction makes up 90% of the total P and the remaining 10% is organic (Figure 16).

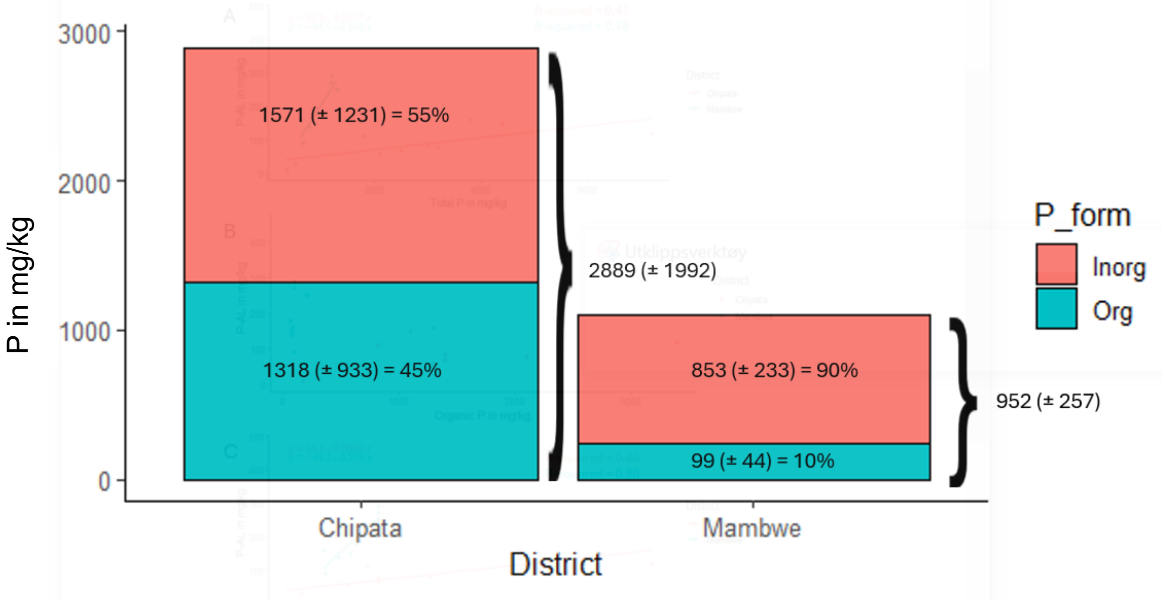


Figure 16: Total P in both districts divided into organic and inorganic indicated with red and blue colors. Y-axis with P content in mg/kg.

Figure 17 is divided into A, B and C with P-AL on the x-axis and total P on the y-axis in A, organic P on the y-axis in B, and inorganic P on the y-axis in C. P-AL increases with an increase in total P following the function y = 35.5 + 0.018 * x in Chipata while the increase is higher in P-AL for increase in total P in Mambwe with y = - 44.5 + 0.248 * x. There is no significant relation between organic P and P-AL. For inorganic P the increase in P-AL is y= 32.5 + 0.033 * x in Chipata and y = -44.3 + 0.276 * x for Mambwe.

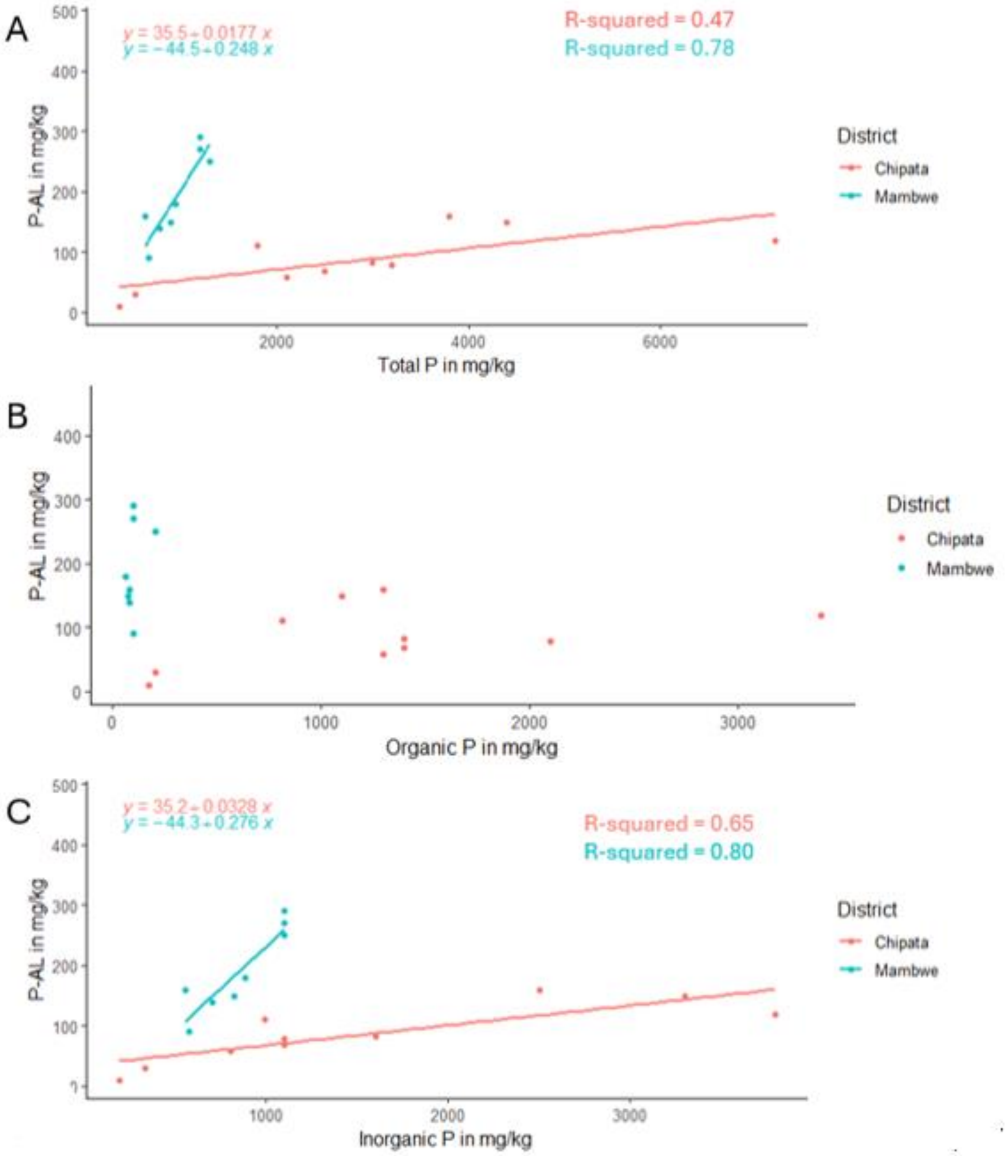
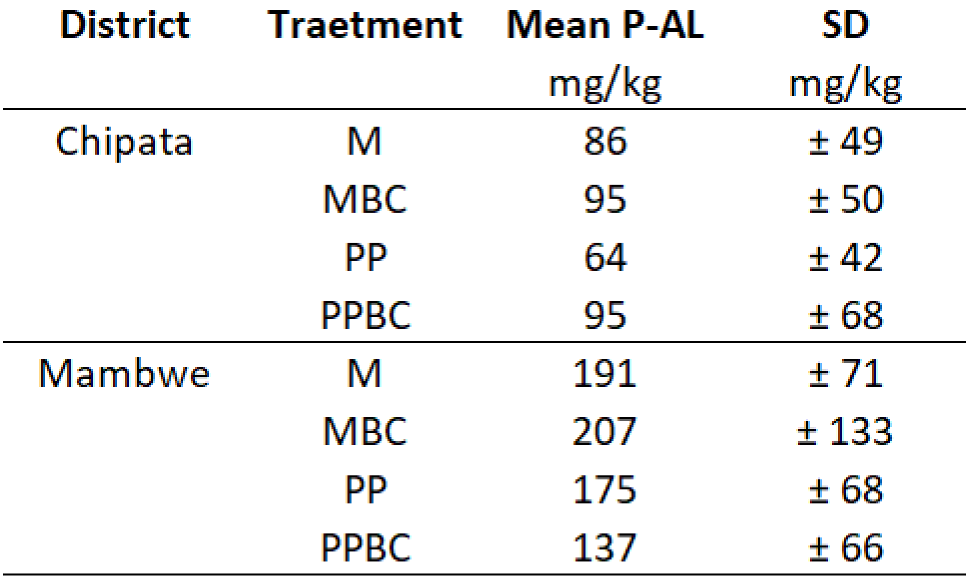


Figure 17: P-AL in mg/kg and total P in mg/kg for A with one linear regression line (y = 35.5 + 0.018x for Chipata and y = -44.5 + 0.248x for Mambwe) for each district with significance ($p < 0.05$) and $R^2 = 0.47$ for Chipata and $R^2 = 0.78$ for Mambwe in A. P-AL in mg/kg and organic P in mg/kg for both districts in B, where no significant relationship was found. P-AL in mg/kg and inorganic P in mg/kg for both districts, with linear regression line for both districts (y = 35.3 + 0.033x for Chipata and y = -44.3 + o.276x for Mambwe) with significance ($p < 0.05$) and $R^2 = 0.65$ in Chipata and $R^2 = 0.80$ in Mambwe.

3.5 P-AL

P-AL ranges from 3.2 mg/kg to 480 mg/kg. The highest value is for MAMB 5 with maize and BC, while the lowest is for farm CHIP 10 with PP and BC. In Table 3 treatment means for both districts are shown, the average varies from 64 mg/kg to 207 mg/kg. P-AL was significantly ($p < 0.05$) greater in Mambwe than in Chipata, but there was no significant effect of treatment (Figure 18 & Appendix C).

Table 3: Average of plant available P (P-AL) in both districts and for all four treatments given in mg/kg.



District	**Traetment**	**Mean P-AL** mg/kg	**SD** mg/kg
Chipata	M	86	± 49
	MBC	95	± 50
	PP	64	± 42
	PPBC	95	± 68
Mambwe	M	191	± 71
	MBC	207	± 133
	PP	175	± 68
	PPBC	137	± 66

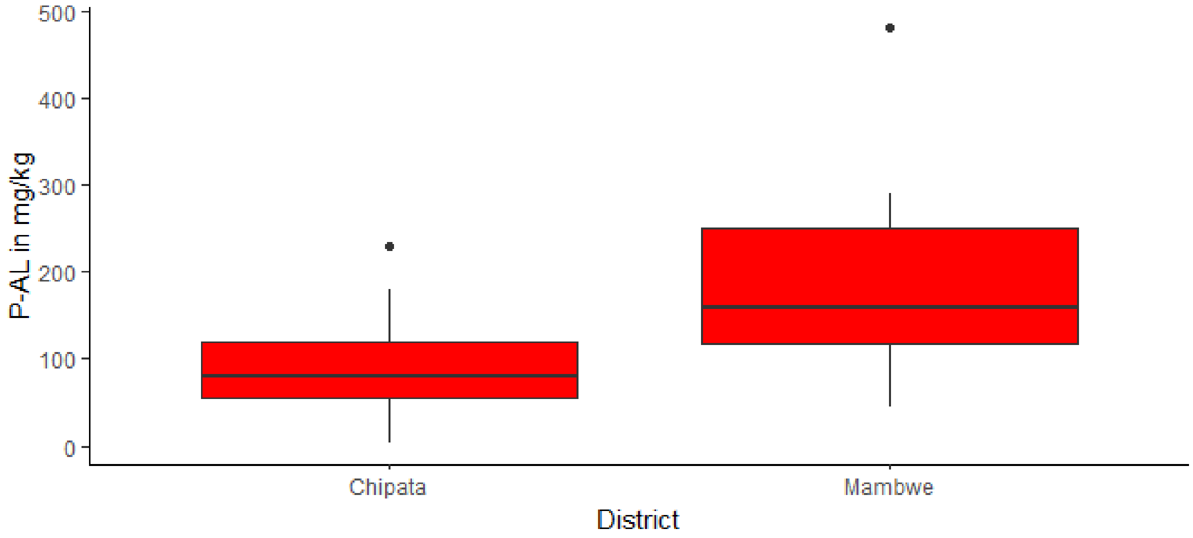


Figure 18: Box-whiskers plot of P-AL in mg/kg on the y-axis and districts on the x-axis.

Figure 19 shows the correlation of P-AL between plots with and without BC on each farm with a linear regression which is significant ($p < 0.05$). The regression line shows that P-AL under maize significantly ($p < 0.001$) increases by 0.62 ± 0.09 per unit increase in P-AL under both maize and BC. The slope was significantly ($p < 0.05$) different from 1, as shown by the 1:1 line added in Figure 19, indicating that farms with high amounts of P-AL in maize plots without BC will have a higher amount of plant available P on corresponding plots with both maize and BC. Low levels of P-AL for plots without BC have lower levels with BC. In contrast, in plots with PP, P-AL without BC increases 1.05 ± 0.17 per unit increase in plots with BC (Figure 20), which is not significantly ($p = 0.76$) different from the 1:1 line.

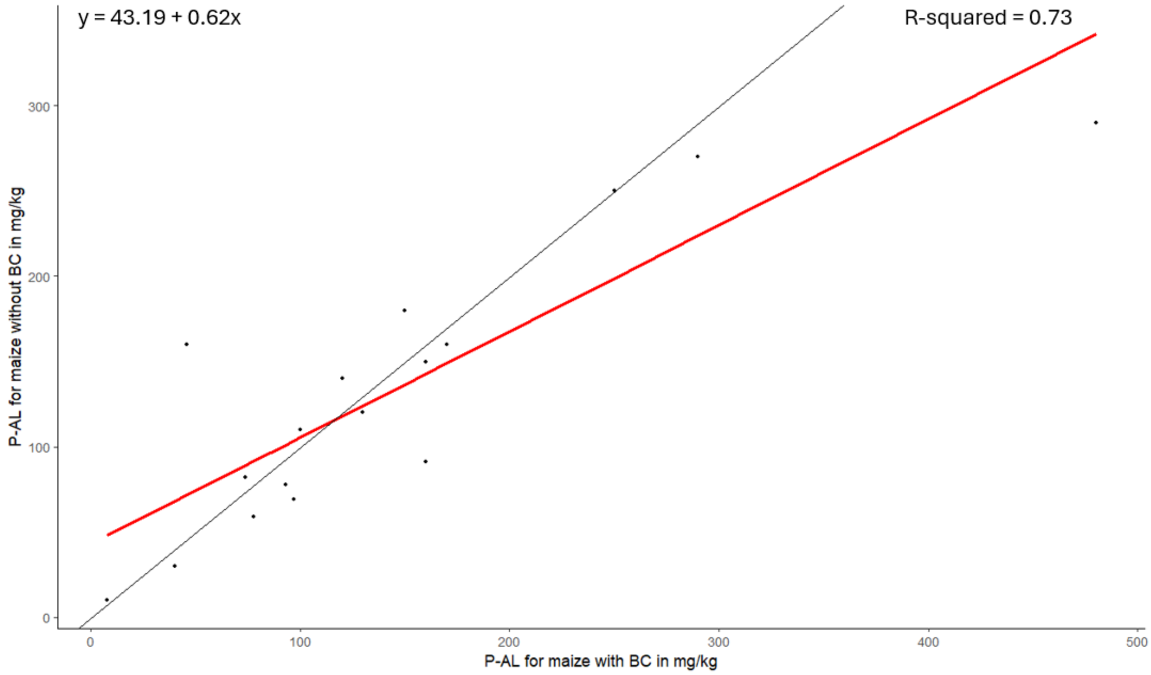


Figure 19: P (P-AL) for plots with maize and BC on the x-axis and plots with maize and no BC on the y-axis, both in mg/kg. The black line is a 1:1 line, and the red line is a linear regression model with the value y = 43.19 + 0.62x, with R-squared = 0.73 and p < 0.05 (n = 18).

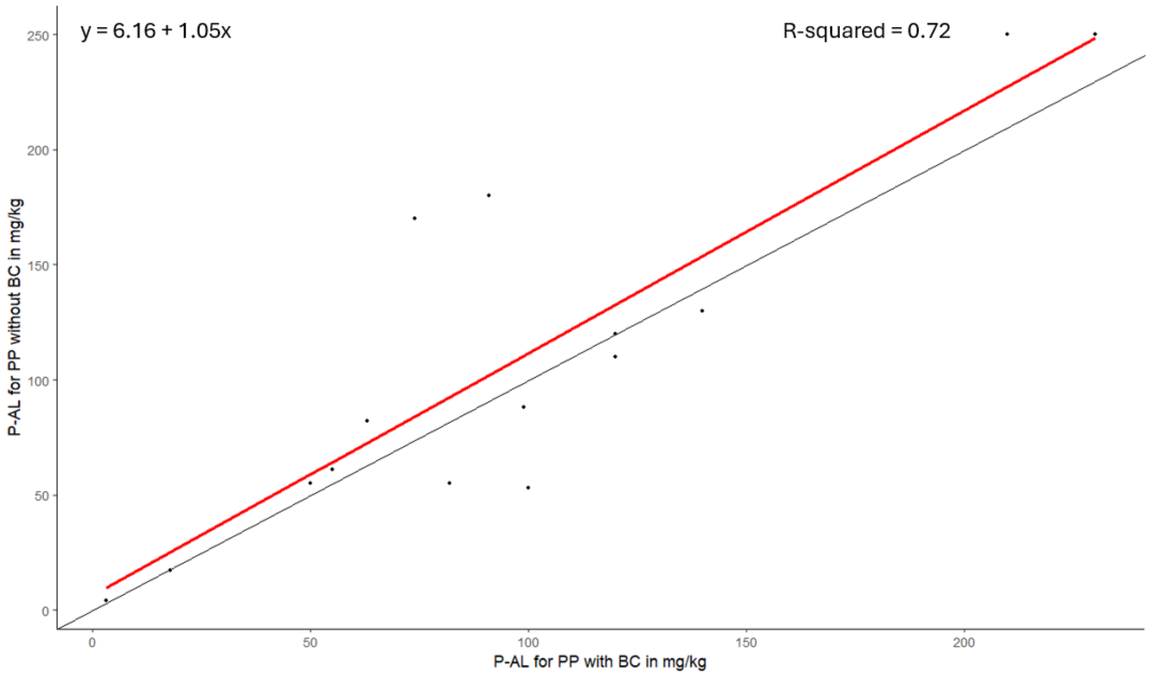


Figure 20: P (P-AL) for plots with PP and BC on the x-axis and plots with PP and no BC on the y-axis, both in mg/kg. The black line is a 1:1 line, and the red line is a linear regression model with the value y = 6.16 + 1.05x, with R-squared = 0.72 and $p < 0.05$ *(n =15).*

3.6 Oxalate extractable Fe, Al and P

The P adsorbed to oxalates was similar in both regions (Table 4). In Chipata, an average of 480 mg/kg was adsorbed to oxalates, and in Mambwe, it was slightly higher with an average of 501 mg/kg. The average of oxalate extractable Al is higher in Chipata with 1605 mg/kg than in Mambwe with 825 mg/kg, while the Fe oxides were closer with 2770 mg/kg and 2700 mg/kg in Chipata and Mambwe, respectively.

Table 4: Average and standard deviation of P_{ox}*,* Fe_{ox} *and* Al_{ox} *in mg/kg for both districts with SD.*

District	**Mean P_{ox}** mg/kg	**SD** mg/kg	**Mean Al_{ox}** mg/kg	**SD** mg/kg	**Mean Fe_{ox}** mg/kg	**SD** mg/kg
Chipata	480	± 350	1605	± 671	2770	± 1125
Mambwe	501	± 211	825	± 328	2700	± 1141

Plotting P absorbed to oxalates with total P (Figure 21) shows different responses in each region. There was a significant ($p = 0.024$) difference in the slope between the two regions. For Chipata, the increase in P adsorbed to oxalates per unit increase in total P is 0.14 ± 0.03, while for Mambwe the increase is a much steeper 0.78 ± 0.25. Note that there was one outlier in Chipata with very low P adsorbed to oxalates on farm CHIP 9.

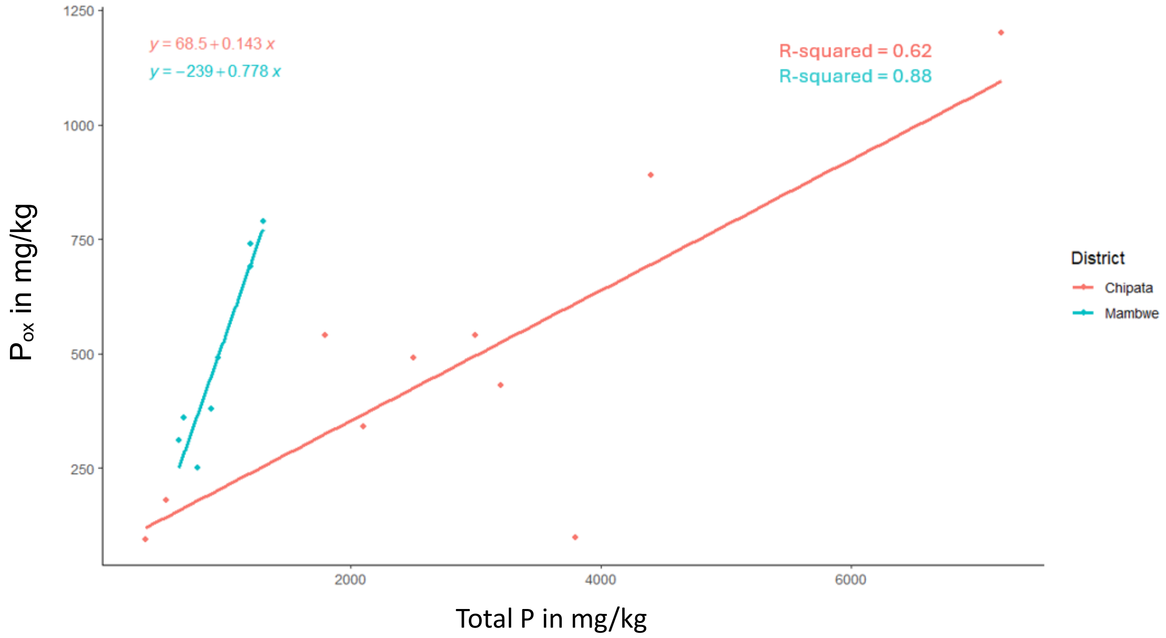


Figure 21: P_{ox} in mg/kg on the y-axis and total P in mg/kg on the x-axis with one linear regression line for each district. The red line and points are for Chipata with regression line y = 68.5 + 0.143x and R^2 = 0.62 (n = 10) and the blue line and points are for Mambwe with regression line y = -239 + 0.778x and R^2 = 0.88 (n = 8).

3.7 C:P

The mean C:P ratio (total C to organic P) differed significantly ($p < 0.05$) between the two districts, as seen in Figure 22. In Chipata, the mean was 28 ± 46, while Mambwe has both greater average and higher variation with 206 ± 60.

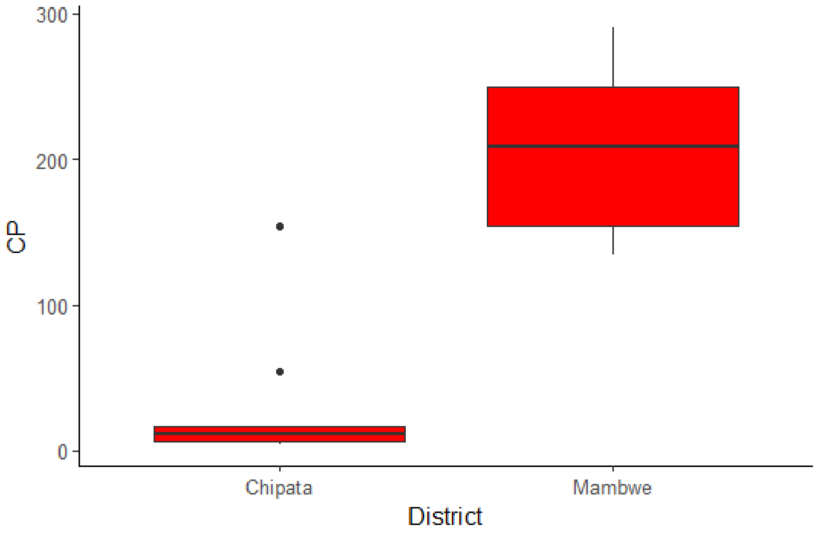


Figure 22: Box-whiskers plots of the C:P ratio on the y-axis and districts on the x-axis.

3.8 Phosphorus saturation degree (PSD)

Phosphorus saturation degree (PSD) is significantly (p = 0.025) different between the districts. In Chipata, the average is 28 ± 14% and in Mambwe, the average is 41 ± 4.7%. The variation is higher in Chipata (Figure 23).

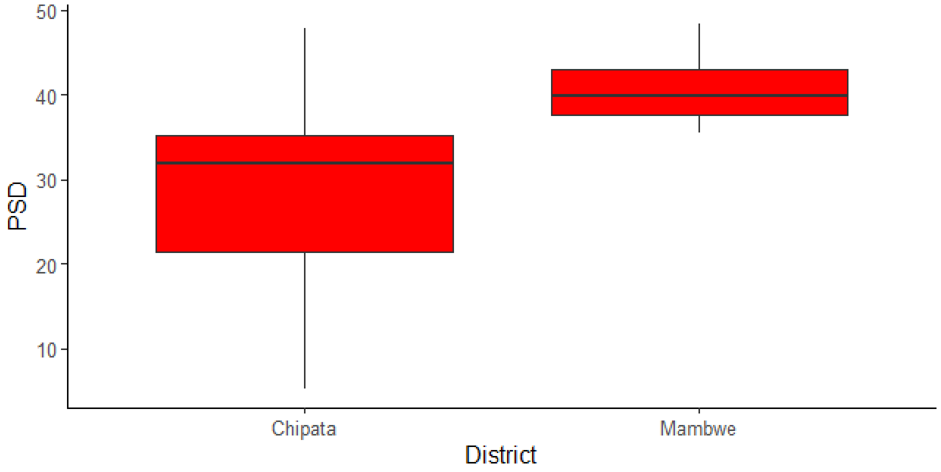


Figure 23: Box-whiskers plots for phosphorus saturation degree (PSD) on the y-axis as % and districts on the x-axis.

4. Discussion

This section will critically discuss the results presented in section 3. The results will be compared to what other studies have found and link the results up to the hypotheses introduced in section 1. Limitations of this study will be presented as well as future work. Lastly there will be some management recommendations.

4.1 pH

The pH ranged from acidic to neutral values across the sampled areas. There is a strong correlation between the pH values in distilled water and $CaCl_2$ solution (Figure 13), which suggests consistency in the pH measurement methods. Plots treated with BC did not show an increase in pH according to the results in this research (Figure 14). Multiple other studies show an increase in pH following the addition of BC (Gondek et al., 2018, Cornelissen et al., 2013). The reason for no effect of BC on pH in the study could be because the amount of BC varied between the farms and too small amounts were added to the fields. Furthermore, the alkalinity of BC (Inyang et al., 2010) might not have influenced the pH because some of the BC was sieved away before the pH analysis. In some plots BC was difficult to locate visually and therefore it is not certain that all the samples from BC treatments had any BC in them. However, even with no significant effect on pH from BC addition, the BC plots, both with maize and PP, had slightly higher pH compared to the corresponding plots without BC.

On the other hand, there was a significant difference in pH between maize plots and PP plots in both regions with PP plots having higher pH (Figure 14). This could be because the maize plots received fertilizers while the PP plots did not. The N fertilizer consist of ammonium and when the plant roots consume the ammonium, they release H^+ to maintain charge balance in the roots. This will decrease the pH in the surrounding soil. Background data shows an increase in pH on both the maize and PP plots (Appendix B) after one year in production. This indicates that there could be an effect on pH from PP because of the N fixating properties. However, studies have shown that legumes typically decrease the pH in surrounding soil due to the N fixating on the root nodules (Yan et al., 1996). Therefore, the explanation could be that the PP crops were still living and being harvested while the maize crops had been harvested and were decomposing on the field. The decomposition of the maize residue will release CO_2, which in turn can decrease the pH, while the PP plots had less organic matter decomposing on the soil, meaning less CO_2 is released in the soil.

Furthermore, there was also an overall higher pH in Mambwe compared to Chipata. Differences in texture could be responsible for some of the differences between the districts. Mambwe has lower sand content, and higher clay and silt content (Figure 12 & Appendix B) meaning that the soil is more resilient to changes in pH. However, it is noteworthy that the magnitude of pH increase varied between districts and treatments, indicating complex interactions influenced by local conditions and management practices.

4.2 Total P

Total P content varied significantly between districts, with Chipata having substantially higher levels (2889 mg/kg) compared to Mambwe (951 mg/kg) (Table 2). The amount of total P was also much higher than what Phiri et al., (2024) found in other soils in Zambia where the range was 52.5 mg/kg – 872 mg/kg and above what Martinsen et al., (2017) found in the Chipata district with 555.55 mg/kg. The disparity between districts was mirrored in the distribution of the organic and inorganic fractions of P with 54% of the total P was inorganic and 46% was organic (Figure 16). This is similar to results from Martinsen et al., (2017), where 35%-50% of total P was organic P under CF in Zambia's Eastern province. On the contrary, Mambwe had a dominance of inorganic P making up 90% of total P and organic P making up the remaining 10% (Figure 16). Since the total P, organic P and inorganic P were analyzed only for the plot with maize and no BC on each farm, the observations do not reveal anything about the effect of BC and crop rotation on these fractions.

However, retention of crop residue from PP and maize will likely increase the total P over time. This would also alter the ratio of organic to inorganic P with the organic fraction increasing. For BC treatments the P content of the BC could increase the total P pool in the soil and organic P fraction of the tot P depending on the P content of the BC. The theoretical increase in soil P from BC was calculated by finding the amount of P in the BC (430 mg/kg) (Intani et al., 2018), volume of the soil per quadrant (125 m^3), amount of BC added to each quadrant (250 kg), and bulk density of the soil (1.34 g/cm^3 in Chipata, and 1.27 g/cm^3 in Mambwe) using the formulas (IV - VII):

IV. $Volume\ of\ soil\ (m\hat{}3) = length\ (m) * width\ (m) * depth\ (m)$

V. $Amount\ of\ P\ added\ (mg) = concentration\ of\ P\ in\ BC\ \left(\frac{mg}{kg}\right) * Mass\ of\ BC\ (kg)$

VI. $Volume\ of\ the\ soil\ (kg) = volume\ of\ the\ soil\ (m^{\wedge}3) * bulk\ density\ \left(\frac{g}{cm^3}\right) * 1000$

VII. $Increase\ in\ soil\ P\ \left(\frac{mg}{kg}\right) = \frac{amount\ of\ P\ added\ (mg)}{volume\ of\ soil\ (kg)}$

Only 10% of the total area received BC (Martinsen et al., 2014) and these calculations gave a theoretical increase of 65 mg/kg in Chipata and 68 mg/kg in Mambwe. These changes are incredibly small compared to the total P (2889 mg/kg in Chipata and 951 mg/kg in Mambwe) in the soils and therefore detecting these changes are difficult.

Even though BC addition and crop rotation did not show any significant effects on total P, inorganic P, and organic P they are useful to compare with the available fraction of P (P-AL). As expected, P-AL increased significantly ($p < 0.05$) with an increase in total P. The same is true for inorganic P, where there was a significant increase ($p < 0.05$) but for organic P there was no significant increase in either district (Figure 17). For total P and inorganic P, the increase in P-AL per unit change in total P and inorganic P were higher in Mambwe than in Chipata, indicating that smaller P inputs in Mambwe are needed to increase P-AL. This could be because the PSD is lower in Chipata (Figure 23) meaning that more P could be sorbed to Fe and Al oxides in Chipata before increasing P-AL. When the Fe and Al oxides are more filled and PSD is increased the expectation is that P-AL would increase more rapidly with an increase in total P, more similar to what is seen in Mambwe.

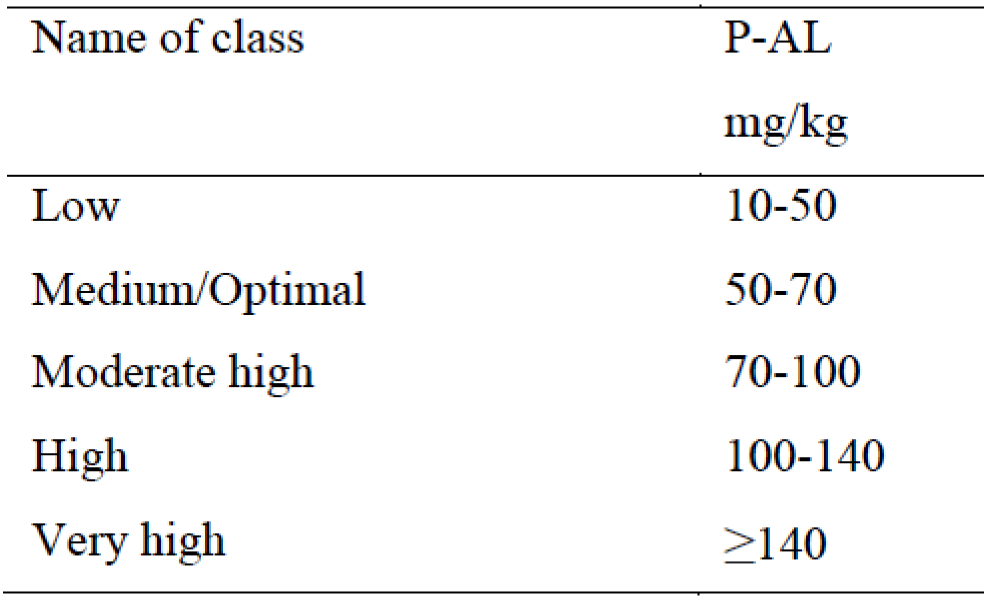
4.3 P-AL

Unexpectedly high amounts of plant available P were found in both regions and all treatments. The mean P-AL values for each treatment in Chipata were ranged from 64 mg/kg - 95 mg/kg (Table 3) which is considered as “moderate high” according to the P-AL classification presented in Table 5. Some of the farms had lower amounts of P-AL and on the farm with the lowest P-AL in Chipata (CHIP 10) all plots had less than 10 mg/kg giving them lower values than the lowest classification “low” in Table 5. In Mambwe, the mean P-AL values for each treatment ranged 137 mg/kg - 207 mg/kg (Table 3) and most farms fall into the very high category which is more than 140 mg/kg P-AL. These amounts of plant available P are a lot higher than another study in Chipata by Phiri et al., (2024) which found 6 mg/kg - 8 mg/kg available P, which is considered “low” according to Table 5. A study from Martinsen et al. in 2017 also found much lower values for available P in the Eastern Province of Zambia with 5mg - 9 mg/kg, but these values are from Bray-P and cannot be directly compared to P-AL (Martinsen et al., 2017). The following formula (VIII) is therefore used to convert Bray to P-AL

VIII. $$PAL\left(\frac{mg}{kg}\right)=\frac{Bray\ P\left(\frac{mg}{kg}\right)-3.49}{0.98}$$

After the conversion the Bray-P reported by Martinsen et al. corresponds to 1.5 – 5.6 mg/kg P in P-AL terms, meaning that the difference between those results and the P-AL reported in this thesis is even wider.

Table 5: Classification levels of P-AL from low to very high based on optimal P for plant growth (Krogstad et al., 2008)



Name of class	P-AL mg/kg
Low	10-50
Medium/Optimal	50-70
Moderate high	70-100
High	100-140
Very high	≥140

The difference in plant available P in each district is opposite from the difference in total P in each district with Mambwe having higher P-AL. This suggests that the districts have different phosphorous cycling dynamics where higher amounts of total P in Chipata do not reflect in the plant available P, which partly can be explained by the difference in pH.

However, the effect of BC and crop rotation on plant P availability is not seen in either district, thereby weakening the first and second hypothesis that BC addition and crop rotation will increase plant available P in the soil. This could be due to high amounts of background levels of available P in the soil which had a range of 9 mg/kg – 303 mg-kg (Appendix D). These values are from Bray-P and must be converted using formula VIII. After the conversion the range is equal to 6 mg/kg – 306 mg/kg P-AL. The high amount of available

P makes it hard to detect relatively small changes. Low amounts of BC in the soil samples due to sieving in the field could also be a reason why there is no observed effect of BC on plant available P.

There was no observed effect on P-AL between PP treatments and M treatments without BC (Appendix E), which correlates with findings in a greenhouse study by Phiri et al., (2024) where PP did not increase P availability. However, future seasons could see an increase in P-AL from PP with the retention of plant residue because of the ability of PP to utilize Fe-bound P in the soil that is unavailable for most plants (Ae et al., 1991). Over time this extra uptake of P from PP would increase the organic P pool in the topsoil if plant residue is not removed from the fields. Subsequently, this could increase the P availability with microbial mineralization over time.

4.4 Oxides

Oxalate-extractable P, Al, and Fe provide further insight into the nutrient cycling and soil fertility dynamics. The oxalate-extractable P and Fe showed comparable levels between districts, while variations in Al content were evident (Table 4). Chipata exhibited higher levels of Al oxides compared to Mambwe, which could influence nutrient retention capacity. The increased amount of Al oxides gives a lower PSD in Chipata (Figure 23) and soil P in Chipata therefore has a higher probability of being sorbed to the oxides leading to immobilization. The results show higher levels of PSD than what Martinsen et al., (2017) found in Chipata which was in the range 15-19%. Higher PSD has been shown to increase P availability in the soil (Wu et al., 2022), but, in this study there was no significant relationship between PSD and P-AL (Appendix F1). However, a significant relationship ($p < 0.05$) between PSD and P-AL is found when farm CHIP 9 is removed. CHIP 9 has a low value for oxalate-extractable P, which will give a low PSD, and the reason is unknown but could be from contamination or imprecise laboratory measurement of the sample.

4.5 C:P

There was a considerable difference in the C:P ratio between the two districts due to the large difference in organic P, which was much lower in Mambwe than in Chipata. However, both districts have a lower mean than what is required for net microbial immobilization of P; C:P = 300 (Arenberg & Arai, 2019). This indicates that the organic P will be mineralized by microorganisms in the soil and become plant available P over time. Compared to what Phiri et al. (2013) found in Zambian soils the C:P ratio in Mambwe is quite similar to multiple other locations like Kashinka, Makeni and Mushemi. However, in Chipata, the C:P ratio is much lower than any other location found in Phiri's study (Phiri et al., 2013), because there was small amounts of organic P in Mambwe.

4.6 Study limitations

One big limitation of the study was that the farmers did not all have enough BC to cover the planned BC plots. This was accounted for by only sampling the area of the plot where BC was found by digging in the soil. Furthermore, the amount of BC added differed between farms. The farmers were in control and may have added the BC at different depths or at different times. If the BC is just added in the top 10 cm of the soil, there is a higher probability of the biochar to be eroded away. And if the BC was added deeper 20 cm the BC would not have been included in the soil samples. Some farmers used chemical fertilizers that were supposed to be added to the trail plots on their other crops, so the amount of fertilizer added varied between farms. Especially in the Mambwe district, multiple farmers did not follow the fertilization plan.

Moreover, the soil samples were sieved in the field right after the bulked samples were collected, and this made the sieving less accurate. Some BC fragments were filtered out and therefore not accounted for in the laboratory analysis and results. This would have a direct effect on C content in the soil, and it could also have an effect on pH, P-AL, total P and organic P.

Furthermore, some farmers in Mambwe left the study group making the sample size smaller. Because of the smaller sample size, randomness in measurements and analysis had bigger impact on the results than what would be the case if all farmer participated fully.

Lastly, there were also two farms in Mambwe where one plot was used for sunflowers, and therefore only maize with and without BC was used in this study from these farms. Again, this reduced the sample size and had a similar impact on the results as the previous limitation.

4.7 Future work

Future work is still to be done to fully understand the effects of crop rotation with PP and BC addition on soil P availability. Over multiple seasons the effects are unknown and must be studied to gain a deeper understanding. To ensure that the participants on the farms are willing to continue, they should be consulted on their experiences and their opinions should be taken into consideration if similar studies are to be conducted. The goals of the farmers and the researchers should be aligned, and cooperation is crucial to ensure a sustainable implementation of alternative agricultural methods like CA.

New studies with higher participation would be important to reduce the effects of randomness in the results. This would give a better understanding and less uncertainty on the real effects of BC and crop rotation on soil P in Zambia.

The methods used should be improved. Especially the sieving of BC should not be done in the field. The method for measuring available P used in this study was P-AL, but the use of Bray-P should be considered since multiple other studies use Bray-P.

4.8 Management recommendations

For the farms in Chipata where there is a lot of potential for sorption of P to Al and Fe oxides fertilizing would not necessarily increase the yield. However, in Mambwe where these seats are taken, fertilizing could increase the P availability immediately. For Chipata, the sorption problem could be solved with the addition of BC, which would increase pH and therefore make the P less likely to be sorbed to Fe and Al oxides. It would be advantageous to continue CA to prevent further land degradation.

5. Conclusion

This thesis has presented the work done in analyzing the effects on P-AL and soil dynamics with the CA methods of BC addition and crop rotation with PP. 18 farms in the Chipata and Mambwe districts of Zambia participated in the multi-year experiment, where crop rotation was done on plots with and without BC. It was hypothesized that:

1. BC would increase the plant available P in the soil, and
2. Crop rotation with PP would increase plant available P in the soil.

Soil samples were taken and brought to Norway for laboratory analysis, identifying and measuring soil properties, pH, total P, inorganic P, organic P, P-AL, oxalate extractable P, Fe and Al, C:P ratio, and PSD.

Considering the first hypothesis, the addition of BC to the soil increased pH, but this increase did not significantly increase P-AL. This weakens the first hypothesis. However, it could be that small changes in P-AL simply were not detectable due to the already high levels of P-AL in the soil.

Similarly, crop rotation with PP also increased pH but there was no effect on P-AL, so the second hypothesis is also weakened. However, this was the first year of cultivation of PP, so the full effect of crop rotation is probably still not detectable.

As for the differences between the two districts, they varied in total P content with Chipata having a larger pool, but this did not reflect in P-AL where Mambwe had more. There was also a bigger increase in P-AL per unit increase of total and inorganic P in Mambwe suggesting that smaller P inputs are needed to increase plant available P. Furthermore, PSD was lower in Chipata than in Mambwe, so the new P input in Chipata is more likely to be sorbed to Al and Fe in the soil. However, the positive effect of BC and crop rotation with PP on pH could make it less likely for P to be sorbed to Fe and Al in the soil thereby increasing P availability.

There is still a need for further work on this subject, and new data should be collected for future years to see how the BC and crop rotation will affect the soil P over time. This will contribute to a growing knowledge base in the field of CA, supporting the mission to improve agricultural practices, increasing yields, and decreasing world hunger.

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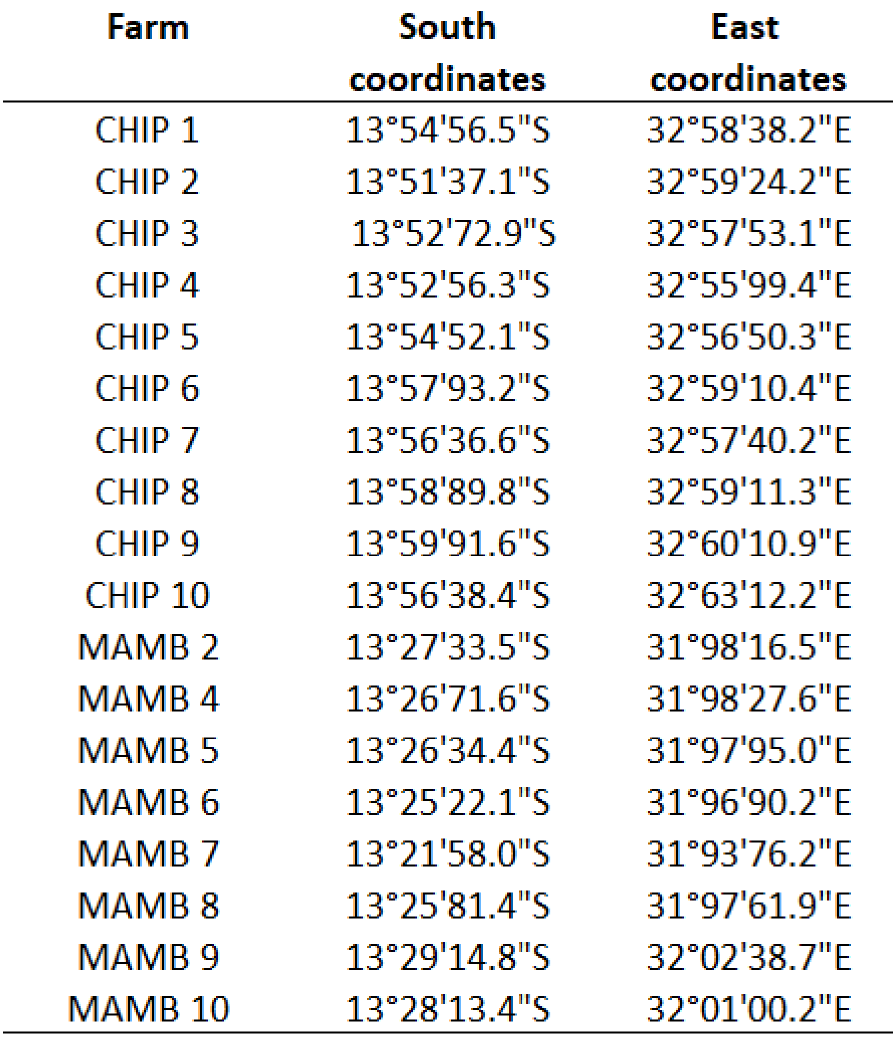
7. Appendix

7.1 Appendix A

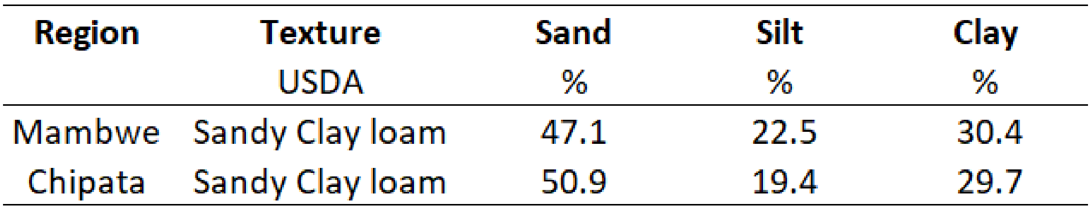
Table A1: Coordinates of all 18 farms included in the study.



Farm	South coordinates	East coordinates
CHIP 1	13°54'56.5"S	32°58'38.2"E
CHIP 2	13°51'37.1"S	32°59'24.2"E
CHIP 3	13°52'72.9"S	32°57'53.1"E
CHIP 4	13°52'56.3"S	32°55'99.4"E
CHIP 5	13°54'52.1"S	32°56'50.3"E
CHIP 6	13°57'93.2"S	32°59'10.4"E
CHIP 7	13°56'36.6"S	32°57'40.2"E
CHIP 8	13°58'89.8"S	32°59'11.3"E
CHIP 9	13°59'91.6"S	32°60'10.9"E
CHIP 10	13°56'38.4"S	32°63'12.2"E
MAMB 2	13°27'33.5"S	31°98'16.5"E
MAMB 4	13°26'71.6"S	31°98'27.6"E
MAMB 5	13°26'34.4"S	31°97'95.0"E
MAMB 6	13°25'22.1"S	31°96'90.2"E
MAMB 7	13°21'58.0"S	31°93'76.2"E
MAMB 8	13°25'81.4"S	31°97'61.9"E
MAMB 9	13°29'14.8"S	32°02'38.7"E
MAMB 10	13°28'13.4"S	32°01'00.2"E

7.2 Appendix B

Table B1: Soil classification according to USDA and mean sand, silt and clay content for Chipata and Mambwe



Region	Texture USDA	Sand %	Silt %	Clay %
Mambwe	Sandy Clay loam	47.1	22.5	30.4
Chipata	Sandy Clay loam	50.9	19.4	29.7

7.3 Appendix C

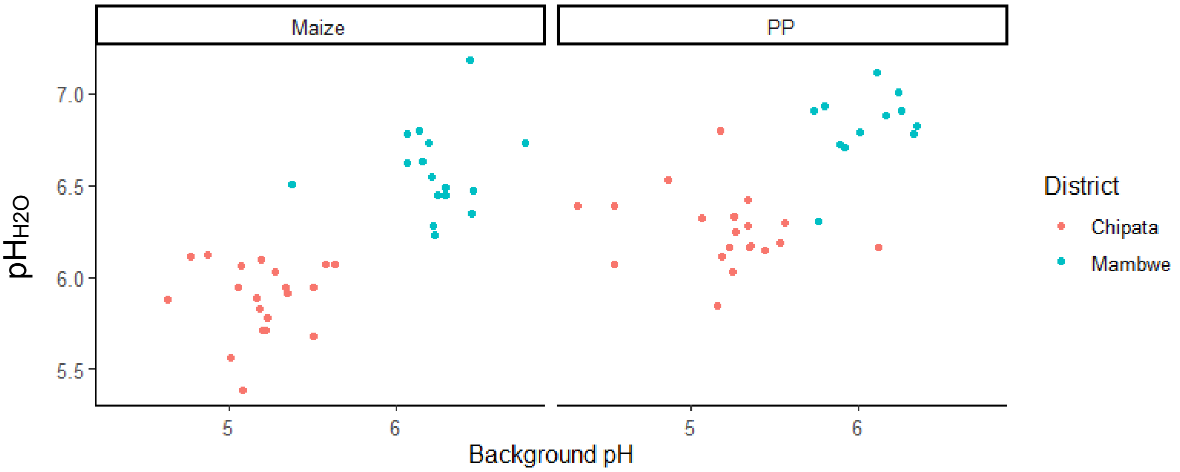
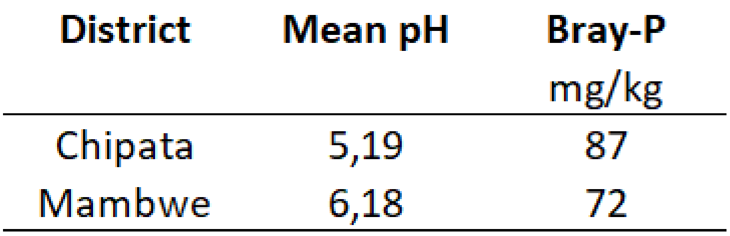


Figure C1: Scatterplot of pH measurements done in this study on y-axis and pH from background data on x-axis with one plot for PP and one for maize. The two districts are separated by color, with Chipata in red and Mambwe in blue.

7.3 Appendix D

Table D1: Mean pH and Bray-P for each district from the background data.



District	**Mean pH**	**Bray-P** mg/kg
Chipata	5,19	87
Mambwe	6,18	72

7.4 Appendix E

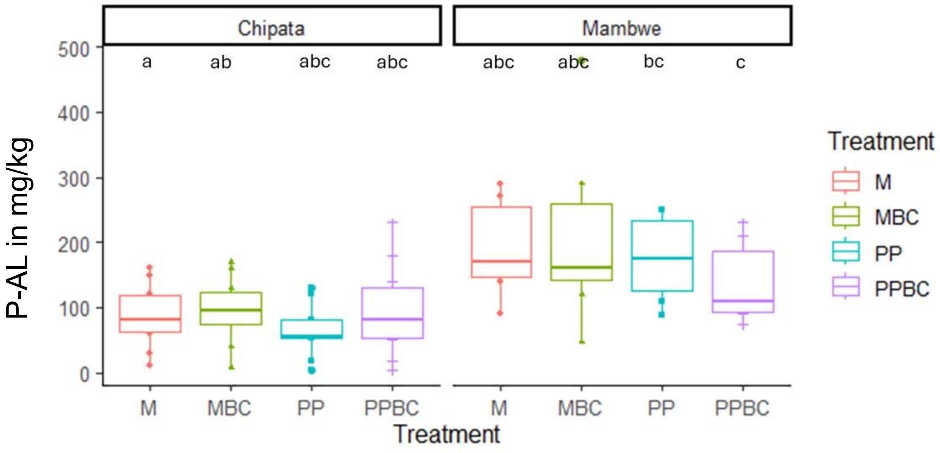


Figure E1: Box-whiskers plot of P-AL for each District in both regions. Lower case letters at the top indicate groups of significant differences (p < 0.05).

7.5 Appendix F

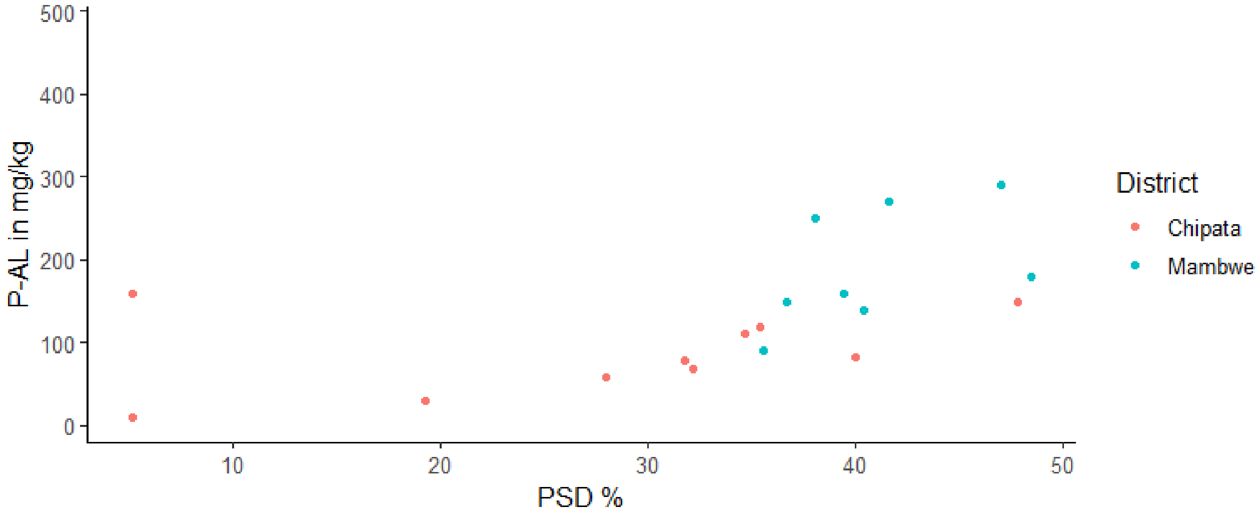


Figure F1: Scatterplot of PSD in % on x-axis and P-AL in mg/kg on y-axis with the two districts separated by color, with Chipata in red and Mambwe in blue.

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