Abstract

Effects of different biochar application rates on soil fertility and soil water retention in on-farm experiments on smallholder farms in Kenya

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Biochar is produced through pyrolysis, the thermo-chemical degradation of biomass under anaerobic or oxygen-limited conditions. Due to its properties related to surface area and porosity, bulk density, nutrient content, stability, cation exchange capacity (CEC), pH value, and carbon content, biochar has the potential to improve physical as well as chemical soil properties and thus improve crop productivity and contribute to carbon sequestration. This study determined the effects of four different biochar rates on retention of plant available soil water, soil bulk density and availability of macronutrients. The research was conducted on smallholder farms in two counties in Kenya, namely Siaya and Embu. Maize cobs and stover biochar was applied in Siaya and coffee husk biochar was applied in Embu. Spectra of soil samples and maize leaves were taken with a visible near infrared (VNIR) spectroradiometer in order to determine soil moisture and available macronutrients. Also, bulk density and soil moisture at different suction pressures were determined.

Regarding plant available water, a trend of increasing soil moisture with biochar rate and significance for the two highest biochar rates compared to control was found in Siaya. For soil moisture at different water tensions, a notable difference between presence and absence of biochar was observed at the two lower water tensions (pF of 1.7 and 3) in Siaya, but not on a significant level. No significant differences or trends in plant available water were observed in Embu. For bulk density, no trend for decreasing bulk density with biochar rate was found and significant differences found were not conclusive for both Siaya and Embu. As to availability of macronutrients, no conclusive significant differences and trends for increasing nutrient content of maize leaves with biochar rate were found in either Siaya or Embu.

Keywords: biochar, soil water retention, bulk density, macro nutrient availability, VNIR, maize cobs and stover, coffee husk

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Popular science summary

This study looked into the effect of biochar, at four different rates both without and combined with fertiliser, on soil water characteristics, soil fertility and plant nutrient status. Plant available water (soil moisture and soil water retention), bulk density, uptake of the macronutrients nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) and moisture content of maize leaves in field have been determined. Maize cobs and stover biochar was applied in Siaya and coffee husk biochar was applied in Embu. The soil found in both sites is a clay rich Nitisol. This study was conducted in Kenya, the two investigated farms are located in the counties Siaya and Embu. Both counties are confronted with food insecurity due to insufficient food production, unreliable rainfall, expensive farm inputs and poor soils. These circumstances call for measures in order to increase soil fertility and as a result, improve food security in the affected regions.

Biochar is produced through pyrolysis, the thermo-chemical degradation of biomass under anaerobic or oxygen-limited conditions. Biochar's physical, chemical and nutritional properties depend on the chemical composition of the feedstock used, pyrolysis system and production conditions. Due to biochar's surface area and porosity, bulk density, nutrient content, stability, cation exchange capacity (CEC), pH value and carbon content it is expected to improve water retention, nutrient retention and plant uptake of nutrients.

As expected, the application of biochar had effects on plant available water in soil. For Siaya, a trend for increasing soil moisture with biochar rate was found. In addition, a notable difference in soil moisture at different water tension for soil samples that received biochar treatments compared to control soil samples was found, although not on a significant level. Contrary to these findings, no significant differences or trends in plant available water were observed in Embu. Both for Siaya and Embu, bulk density did not decrease with biochar rate, as has been previously assumed. Considering availability of macronutrients the expectation of increasing nutrient content of maize leaves following biochar addition could not be confirmed for both sites.

The absence of the expected outcomes for a large portion of investigated properties, may be due to influences of soil texture, physical and chemical properties of biochar type, lack of field ageing, application rate and crop effects. In addition, the limited time since experiment establishment and the limited number of analysed samples might contribute to that.

In conclusion, it became clear that in order to allow for accurate prediction of the effects of biochar towards soil characteristics and nutrient availability a deeper unterstanding of interactions between soil type, biochar production method, biochar feedstock, application rate and field crops is essential.

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Abbreviations

AWC	Available Water Capacity
CEC	Cation Exchange Capacity
DAP	Diammonium Phosphate
FC	Field Capacity
IITA	International Institute of Tropical Agriculture
K	Potassium
MC	Moisture Content
N	Nitrogen
P	Phosphorus
PWP	Permanent Wilting Point
RCBD	Randomised Complete Block Design
S	Sulphur
SLU	Swedish University of Agricultural Sciences (Sveriges lantbruksuniversitet)
SOM	Soil Organic Matter
VNIR	Visible Near Infrared

1 Introduction and Objectives

This thesis is carried out as a part of the 3-year project “Bio-char and smallholder farmers in Kenya - improved use efficiency of farm-level organic resources in relation to energy, crops and soil”. The project is performed by a team of scientists from the International Institute of Tropical Agriculture (IITA), the Swedish University of Agricultural Sciences (SLU), Lund University and the World Agroforestry Centre (SLU, 2015).

1.1 Aim and Hypotheses

The aim of this study is to determine how biochar amendment of soil with four different rates both without and combined with fertiliser, in total eight treatments, affect soil water characteristics, soil fertility and crop nutrient content in crop fields on smallholder farms in Kenya. In order to determine the actual effects of the treatments soil moisture, soil water retention, bulk density, plant nutrient status regarding nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) and moisture content of maize leaves in field have been measured.

The working hypotheses of this study are that amendment of soil with biochar, especially with increasing application rate, leads to:

1) Improved retention of plant available soil water
2) Decrease in soil bulk density
3) Improved macro nutrient availability

1.2 Background Details and Problems at investigated Sites

Soil samples were taken at two farms in Kenya, one farm is located in Western Kenya (Siaya County) and the other farm is located in Central Kenya (Embu County).

Table 1: Location of experiment sites.

Province	County	District	Location	Village
Western Kenya	Siaya	Gem	Yala	Nyabeda
Central Kenya	Embu	Embu North	Kibugu	Kibugu

Figure 1: Location of Experiment sites (Google Maps, 2016).

1.2.1 Siaya

Siaya County is located in western Kenya. Its land surface area is 2,530 km^2 and its water surface area stretches over 1,005 km^2, this partly includes Lake Victoria. The total population was estimated to be 890,000 persons in 2012 (Siaya County Government, 2013).

There are two distinct rain seasons in the county, long rains between March and June and short rains between September and December. The amount of rainfall depends on altitude. The rainfall ranges between 800-2000 mm annually for the highlands and 800-1600 mm annually for the lowlands. The county is drier in the western parts and wetter in the higher altitudes in the eastern part, including Gem subcounty. (Siaya County Government, 2013).

Maize is among the main food crops, which also include for example sorghum, millet, beans, cowpeas and cassava. The county is food insecure considering that food production is only sufficient for nine months in a year resulting in a major shortage of food during a lean period for a large proportion of residents. Moreover, since production is not stable in poor seasons food shortage can persist up to eight months. Low production is caused by poor crop husbandry, limited area covered by food crops and high post-harvest losses. Further reasons for food insecurity are unreliable rainfall, expensive farm inputs, use of low quality seeds, poor soils, overreliance on a few crop varieties (mostly maize) and high prevalence of HIV/AIDS in the region. The average size of a small-scale farm is 1.5 ha and for a large-scale farm 7.0 ha in Siaya. Due to the small farm holdings mechanised agriculture is strongly limited (Siaya County Government, 2013).

The soil fertility status is in general poor in the area. Different factors contribute to that, one being that the most fertile soils are mainly found in the climatically less suitable zones (Jaetzold et al., 2010). The main soil type in Siaya is Ferralsol, which shows moderate to low fertility (Siaya County Government, 2013). The soil type at the farm, the investigated area in Siaya, is a dystric Nitisol (Kikuyu red clay loam), which is leached and only shows moderate fertility. The parent material, mudstones and claystones, have limited plant nutrient content. This type of soil is well drained, very deep, red to dark red with friable clay (Jaetzold et al., 2010). For most soils in Siaya there is the need to use organic and/or inorganic fertiliser in order to produce crops. Most areas in the regions feature underlying murram (laterite) with poor moisture retention (Siaya County Government, 2013). In addition, nematodes are a widespread problem and limit the climatically possible yields (Jaetzold et al., 2010).

1.2.2 Embu

Embu County belongs to Eastern Region of Kenya, stretching over an area of 2,818 km^2. The total population was projected to be 550,000 persons in 2013. The county features two distinct areas when it comes to agro-climatic and natural characteristics, which are highlands and lowlands (Embu County Government, 2013). The investigated farm within this project is located in Embu North, which belongs to the highlands.

Embu North as a part of Embu County shows typical characteristics of the windward side of Mt. Kenya. This manifests itself in higher average annual rainfall compared to lowland areas. There are two distinct rain seasons in the County, long rains between March and June and short rains between October and December. The amount of rainfall ranges depending on altitude between 640 mm to 1,495 mm annually for the whole County (Embu County Government, 2013).

Maize is the main food crop, other major food crops are beans, cowbeans, irish potatoes, sorghum, pearl millet. (Embu County Government, 2013).

Embu faces environmental degradation through soil erosion, loss of agro-biodiversity and soil nutrient depletion. Since the county sometimes depends on food supplies regarding staple food, especially in areas in the lowlands, it can be considered as food insecure. Reasons for food insecurity are for example inadequate rainfall, poor terrain, poor soil fertility, small parcels of land, competition of food crops with cash crops for land. The average size of a small scale farm is 0.8 ha (Embu County Government, 2013).

Embu County features five major soil types, namely Nitisols, Andosols, Vertisols, Ferrosols and Cambisols (Ouma et al., 2002). The soil type at the area of the farm where the study was carried out is humic Nitisol (Kikuyu red clay loam). The parent material is basic igneous rock. The soil is well drained, extremely deep, dusky red to dark reddish brown with friable clay and has an acid humic topsoil. The soil has moderate to high fertility, but is vulnerable to leaching by permanent cultivation without fertiliser or manure (Jaetzold et al., 2007).

1.3 Significance and Purpose of Study

Low soil fertility due to various forms of land degradation resulting in food insecurity is a major problem in both areas investigated within this thesis. This problem calls for measures to be undertaken in order to increase soil fertility and as a result, improve overall food security in the affected regions.

Downie & Van Zwieten (2013) also witness that the main factors driving the implementation of new technologies such as biochar or farming systems are challenges like food security, decrease in soil fertility and climate change mitigation. These mentioned challenges also apply to the investigated areas within this study. Moreover, sub-Saharan Africa as a whole is affected by land degradation due to fast population growth and increasing demand for food and energy (Rockström et al., 2009). Thus, improvements in nutrient uptake and nutrient use efficiency of crops are crucial, especially since most farmers in this region face problems in accessing mineral fertilisers (Gwenzi et al., 2015).

In this context, reasons for using biochar as a soil amendment are the same as those mentioned by Downie (2011), namely increasing soil fertility and crop productivity and thus also food and nutrition security and climate change mitigation. Another benefit of soil amendment with biochar is increased predictability of yield, due to lower vulnerability to climatic events like floods and droughts (Sohi et al., 2009). Application of biochar can be seen as an adoption of modern crop husbandry, which is mentioned among the development objectives formulated by Siaya County Government (2013).

2 Literature Review

2.1 Production and Application of Biochar

Biochar, a material rich in carbon, is produced through pyrolysis – the thermo-chemical degradation of biomass under anaerobic or oxygen-limited conditions (Lehmann, 2007a; Lehmann & Rondon, 2006; Chan et al., 2008b). During the process of pyrolysis aliphatic carbon condenses into more stable aromatic carbon and combustible gases (H2, CH4, CO) are released (Waters et al., 2011). The pyrolysis process can be divided into different categories; gasification (>800°C), fast pyrolysis (~500°C) and slow pyrolysis (450-650°C) (Sohi et al., 2009). Slow pyrolysis is the most optimal pyrolysis process for production of biochar over other products (Duku et al., 2011; Sohi et al., 2010).

Biochar's pH, ash content, surface area and microporosity increase and volatile matter decreases with increasing highest treatment temperature (HTT) (Mukherjee et al., 2014, Lehmann & Joseph, 2009, Downie et al., 2009).

There is a long history of biochar application to soils, which includes for example the Terra Preta de Indio soil in Brazil (Sombroek et al., 2002). According to Lehmann & Joseph (2009), the char produced by pyrolysis is only called biochar when its application is towards environmental management and productivity benefits to soil. In addition to biochar's usage as soil amendment, it is also used for carbon sequestration, mitigation of climate change, as a source of bio-energy and for waste management (Lehmann, 2007a; Lehmann and Joseph, 2009). Due to a high proportion of aromatic structures, which results in resistance to chemical and biological decomposition, biochar can remain in the soil for hundreds to thousands of years (Schulz & Glaser, 2012; Lehmann, 2007a).

2.2 Properties of Biochar

The physical, chemical and nutritional properties and thus the quality of biochar depends on the chemical composition of the feedstock used, pyrolysis system and production conditions, including temperature and residence time (Downie et al., 2009; Glaser et al., 2002; Major, 2010a; Gaskin et al., 2008). Important properties of biochar are the high surface area and porosity, low bulk density, nutrient content, high stability, high cation exchange capacity (CEC), neutral to high pH and high carbon content (Berek, 2014). These properties make it suitable as an amendment for tropical sandy and clay soil in sub-Saharan Africa (Gwenzi et al., 2015).

As suggested above biochar has the potential to improve soil properties like water holding capacity, infiltration, soil aeration, root development, soil density, nutrient holding capacity, CEC and pH value (Downie & Van Zwieten, 2013; Atkinson et al., 2010; Chan et al., 2008a; Glaser et al., 2002). By directly influencing soil structure, distribution of pore size and density of soil application of biochar in turn affects water holding capacity, aeration, soil workability and permeability (Downie et al., 2009; Novak et al., 2012, Brady & Weil, 2008). Water retention, nutrient retention and plant uptake of nutrients has also been found to improve due to increase in overall net soil surface area in soil after application of biochar (Chan et al., 2008a; Downie et al., 2009; Lehmann & Joseph, 2009).

Long-term effects like stabilisation of organic matter, slower release of nutrients from organic matter and increased retention of cations are assumed to have a major impact on yield (Lehmann & Rondon, 2006; Brady & Weil, 2008). Overall, biochar's effect on crop production can range from very positive, over neutral to negative. Specific unfavourable crop and soil combinations are responsible for negative effects (Sohi et al., 2009). In the following biochar's properties are explained in more detail.

2.2.1 Surface Area and Porosity

Biochar features a high surface area through a high amount of pores (Lehmann & Joseph, 2009). Although surface area of biochar increases with rising highest treatment temperature, at a certain temperature deformation takes place and in turn decreases the surface area (Lehmann & Joseph, 2009; Downie et al., 2009). The specific surface area of biochar thus varies between <10 m^2 g^{-1} at temperatures below 400°C and up to 400 m^2 g^{-1} at temperatures of 550-600°C (Brown, 2009).

The share of micro- and macropores in biochar depends on the feedstock used and pyrolysis conditions (Lehmann & Joseph, 2009; Tseng & Tseng, 2006).

If biochar contains a high proportion of ash, the porosity of biochar can increase with time when the ash is dissolved and leached from the pores. High ash content may lead to deterioration of structure and thus reduce biochar's stability (Lehmann & Joseph, 2009). Mukherjee et al. (2014) found an increase in ash content after ageing of biochar for 15 months, but only for biochar produced at low temperature.

Surface area and porosity of biochar both determine its water retention, absorption capacity and surface chemistry including CEC (Berek, 2014; Ogawa & Okimori, 2010; Yu et al., 2006). Although according to Sohi et al. (2009) the surfaces of biochar produced at low temperatures are potentially hydrophobic and thus the capacity of water storage in soil might be limited. The water holding capacity of biochar itself varies between 75 to 247 % of its weight (Solaimann et al., 2012).

As the surface area of biochar is similar to the one of clay the application of biochar could give soil more clay characteristics, resulting in beneficial effects on plant growth. Overall, biochar's large surface area and thus porosity has positive effects on soil water characteristics and soil fertility (Lehmann & Joseph, 2009).

2.2.2 Nutrient Content

Biochar usually contains N, P and basic cations like Ca, Mg and K (Major et al., 2010b). Biochar based on plant materials often have lower concentration of nutrients and minerals such as N and P, but a higher C content when compared to biochar based on manure (Lehmann et al., 2003; Chan et al.,2008a; Chan et al., 2008b; Waters et al., 2011).

For plant-based biochar the C and N concentration may increase with increasing pyrolysis temperature and for biochar based on mineral-rich feedstock, like manure, decrease with increasing pyrolysis temperature, since less volatile elements such as P, K, Ca and Mg concentrate as volatiles fade (Gaskin et al., 2008; Singh et al., 2010). In accordance with that Gaskin et al. (2008) found a lower N and higher P, K and Ca concentration for poultry litter biochar produced at a higher pyrolysis temperature (500°C) compared to the same poultry litter biochar produced at a lower pyrolysis temperature (400°C). However, P and K vaporize during pyrolysis at temperatures between 700 and 800°C (DeLuca et al., 2015) and high processing temperatures in general might lead to nutrient loss through volatilization (Jensen et al., 2000; Olsson et al., 1997; Lehmann & Joseph, 2009).

In general, the actual nutrient content of biochar and its bioavailability is highly dependent on the feedstock used and pyrolysis conditions and so far information on the bioavailability of nutrients contained in biochar is rare (Gaskin et al., 2008; Singh et al., 2010).

2.2.3 pH Value and Liming Potential

Various types of biochar exhibit a neutral to alkaline pH value and are consequently suitable for neutralising acidic soils (Waters et al., 2011; Yamato et al., 2006; Gwenzi et al., 2015; Novak et al., 2009a). Although Chan & Xu (2009) state that biochar's pH can also range from slightly acidic to alkaline. According to Lehmann (2007b), the pH value of biochar can range from 4 to 12 depending on feedstock used and pyrolysis condition. The pH value and $CaCO_3$ equivalence of biochar increases with increasing pyrolysis temperature (Singh et al., 2010). Moreover, pH value in biochar increases over time due to surface oxidation in soil (Cheng et al., 2008).

Biochar can function as a liming agent by causing an increase in pH of soil and thus increasing availability of nutrients and improve nutrient uptake by plants for various soil types (Glaser et al., 2002; Lehmann & Rondon, 2006; Lehmann & Joseph, 2009). Biochar's liming potential is dependent on the feedstock used and pyrolysis conditions, which determine ash and carbonate content (Singh et al., 2010; Berek, 2014). In addition, biochar's considerable surface area and functional groups play a role (Berek, 2014).

Kookana et al. (2011) argue that biochar derived from feedstocks richer in ash like animal manure features a higher neutralising capacity than biochar based on wood or greenwaste. Especially biochar produced at high temperature and based on animal manure feedstock is naturally alkaline (Chan et al, 2009). The liming potential is measured as calcium carbonate ($CaCO_3$) equivalents (Van Zwieten et al., 2010b).

2.2.4 Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) is the quantification of the capacity of a material to bind positive charged ions or molecules on negatively charged surfaces like clays and soil organic matter (Brady & Weil, 2008). In other words, CEC is the total amount of exchangeable cations that are bound to a sample of soil and is given as molar equivalents of negative surface charge per weight of soil (Manahan, 2011).

CEC in biochar is dependent on the levels of minerals in the feedstock and pyrolysis temperature at production (Gaskin et al., 2008; Novak et al., 2009a; Nguyen et al., 2010; Singh et al, 2010). Both decrease in CEC with increasing pyrolysis temperature and increase in CEC with increasing pyrolysis temperature were documented (Gaskin et al., 2008; Singh et al., 2010). In general, slow pyrolysis biochar shows an increased CEC due to a higher degree of oxygen surface functional groups (Gaskin et al., 2008). CEC of biochar can range from negligible to 40 cmolc g^{-1}, CEC of biochar has been observed to increase gradually after incorporation in soil due to oxidation (Verheijen et al., 2010). Surface oxidation takes place due to reactions of water, O_2, and several soil agents (Cheng et al., 2006).

Biochar based on plant feedstocks usually shows a lower CEC as biochar based on animal-derived feedstock (Scott et al., 2014).

2.3 Effects of Biochar on Soil Properties

2.3.1 Soil Water Retention and Plant Available Water

Soil texture, aggregation and soil organic matter (SOM) content influence the connectivity and distribution of pores in the soil matrix, which in turn determines soil water retention (Brady & Weil, 2004; Verheijen et al., 2010; Major, 2009; Sohi et al., 2009). Due to biochar's relatively higher surface area and higher porosity compared to other types of SOM it is suitable to improve water retention trough improvement of soil texture and soil aggregation (McElligott et al., 2011; Asai et al., 2009; Brockhoff et al., 2010; Verheijen et al., 2010).

Also Rawls et al. (2003), Glaser et al. (2002), Major (2009) and Sohi et al. (2009) argue that increase in SOM due to biochar treatments has an effect on soil water retention. According to Glaser (2002), soil water retention was 18% higher in *terra preta* soil compared to adjacent soils with low or no charcoal contents. This might be due to effects of charcoal itself and resulting higher levels of SOM.

As for other biochar properties, its effects on soil water characteristics are dependent on feedstock source and processing condition. Due to that, there are different findings in the literature. Novak et al. (2009a) and Chan et al. (2008a) found no significant effect of the application of biochar on water holding capacity. Novak et al. (2009b) found that water retention capacity differed among soils depending on type of applied biochar. Lei & Zhang (2013) and Novak et al. (2009b) confirm enhanced water retention capacity following application of biochar, especially for biochar exposed to higher pyrolysis temperatures.

Water retention curves express soil moisture content at different water tensions. The pF-value is the logarithm of water tension: $pF = \log \psi m$. The permanent wilting point (PWP) is the water content, at which plants irreversible wilt ($pF = 4.2$). Field capacity is the water content that a soil in undisturbed condition can hold in resistance to gravity. The field capacity usually ranges between a pF value of 1.8 to 2.5. For a soil in a state of equilibrium with homogeneous texture and homogeneous structure water content at field capacity increases with depth (Scheffer & Schachtschabel, 1998).

Novak et al. (2009b), Dumroese et al. (2011) and Lei & Zhang (2013) found a significant influence of biochar addition on water retention. Addition of biochar increases soil field capacity, especially at high application rates, resulting in increased plant growth and improved water economy (Alburquerque et al., 2014). Chan et al. (2008a) found in their study that although field capacity increased with increasing rate of biochar addition significant changes could only be observed at higher rates of biochar additions of 50 and 100 t ha^{-1}.

Soil texture is determining initial water content of soil. Especially, following biochar addition, soil texture has a considerable influence on biochars actual effects on water content. In Figure 2, the volumetric water content at different pF-values dependent on clay content is shown.

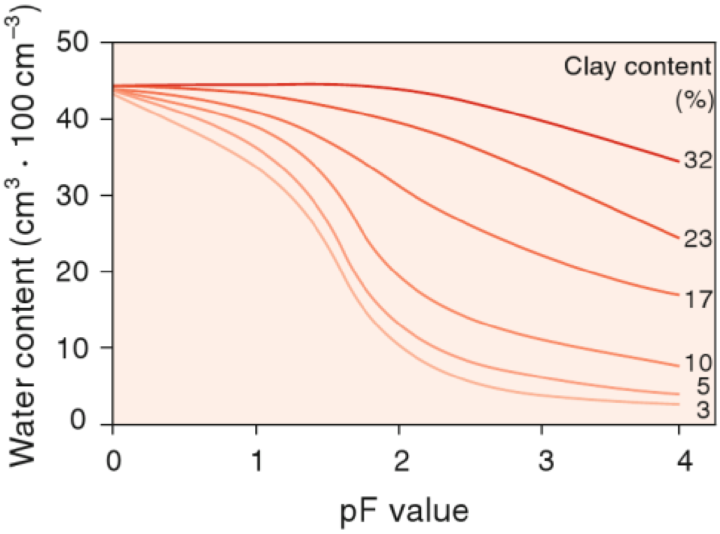

Figure 2: Effect of clay content on the shape of the pF curve in soils with equal pore volume (Scheffer & Schachtschabel, 1998).

Lei & Zhang (2013) observed a significant increase in plant available water and macropores in soil amended with biochar, especially those amended with biochar produced at higher temperatures, as compared to control. Moreover, application of biochar in soil might increase drought tolerance and water use efficiency (Kammann et al., 2011).

2.3.2 Bulk Density and Soil Aggregation

Bulk density of soil might decrease through addition of biochar, especially at high application rates, due to its relatively lower bulk density compared to mineral particles (Lehmann et al., 2011; Brady & Weil, 2004; Alburquerque et al., 2014).

Lei & Zhang (2013) confirm a decrease in soil bulk density and improved soil aggregate structure following biochar application, which led to increased total porosity in soil and increase in macropores and in turn to increased water content at low suction pressures. Changes in soil porosity are caused by biochar’s interaction with organic particles or parent soil minerals (Lehmann et al., 2011). Especially biochar exhibiting low density (300 kg m^{-3}) and highly stable organic carbon is expected to reduce soil bulk density and thus increase total soil porosity (Gwenzi et al., 2015).

Moreover, decrease in soil bulk density following the application of biochar can positively influence root development and growth (Atkinson et al., 2010; Laird et al., 2010). Alameda & Villar (2012) argue that high soil bulk density might negatively influence plant growth.

Soil compaction might not be reduced in the short term, but in the long term since biochar's properties in soil and hence soil quality are influenced by ageing (Cheng & Lehmann, 2009; Hale et al., 2011; Lin et al.,2012; Mukherjee et al., 2014).

The organic carbon in biochar might be crucial for enhancing soil aggregation and aggregate stability. As a further consequence, changes in soil structure might improve soil moisture retention, infiltration and lead to a reduction in runoff and erosion (Gwenzi et al., 2015). Biochar's effect on soil aggregation is also linked to its surface charge characteristics (Cheng et al., 2006). As for other soil properties, soil aggregation might only be enhanced in the long term and not immediately after application (Mukherjee & Lal, 2014).

2.3.3 Nutrient Properties of Soil

Nutrient availability and nutrient use efficiency in soil directly increases through the addition of nutrients contained in biochar and indirectly through improved nutrient retention, modified soil microbial dynamics and increased decomposition of organic material in soil (Lehmann et al., 2003; Lehmann & Joseph, 2009; Lehmann & Rondon, 2006; Sohi et al., 2009).

Biochar retains nutrients through capturing of nutrient containing water in its micropores, which is held by capillary forces. Biochar particles are assumed to act like clay and thus hold large amounts of immobile water even at increased matric potentials. Consequently, nutrients dissolved in this immobile water would be kept near the soil surface and would be available for plants (Major et al., 2009). In addition, through adsorption of cations and anions by biochar leaching of applied nutrients is reduced (Major et al., 2009). Increased cation exchange capacity (CEC) following biochar application is resulting in increased nutrient and fertiliser retention (Lehmann et al., 2003; Lehmann & Joseph, 2009; Liang et al., 2006; Major et al., 2009).When CEC increases, fertilisers applied to the soil can be adsorbed to biochar's surface area and consequently easier used by the plants (Steinbeiss et al., 2009).

Downie (2011) and Van Zwieten (2010a) confirm biochar's important role in improving N-fertiliser use efficiency. According to Sohi et al. (2009) when fertiliser is applied with biochar, the same crop yield can be achieved with a lower fertiliser application rate. Asai et al. (2009) and Steiner et al. (2007) observed a remarkable lower yield with biochar only addition compared to simultaneous application of biochar and fertiliser leading to yield increase due to sorption and reduced leaching of nutrients.

According to Lehmann & Rondon (2006) high biochar application rates in a tropical environment led to increased uptake of P, K, Ca, Zn and Cu by plants. Steinbeiss et al. (2009) observed an increase in plant uptake of P, K and Ca after biochar application. According to Chan et al. (2008a), N as a limiting factor might be detrimental to the efficiency of P and K added to soil by biochar.

Soil amendment with biochar is recommended in particular for reducing nutrient leaching losses in areas with high rainfall (Major et al., 2009). Dempster (2013) argues that environments with higher rainfall allow dissolution and diffusion of P and K and observed that in drier environments biochar’s impact is strongly influenced by rainfall and that biochar’s influence might only be sporadic in drier environments.

2.3.4 pH Value and Liming Potential

Biochar with a high liming equivalence typically increases the pH value in acidic soils, whereas the actual increase is dependent on the pH-buffering capacity of the respective soil (Mukherjee & Lal, 2014). The liming effect of biochar is positive for acidic soils, especially if they are affected by metal toxicity or nutrient deficiencies. Further, pH in soil increases more when biochar rich in ash is used. In case of disproportionally high soil pH values, liming effect can also have adverse effects (Alburquerque et al., 2014).

The increase in pH value following biochar application is usually higher in sandy and loamy soils than in clayey soils (De Gryze, 2010). The buffering capacity of a finely textured clay soil is usually higher than that of a coarse-textured soil. This entails that larger amounts of liming resources for clayey soils are required in order to raise the pH to a certain value when compared to a soil with low buffering capacity (CTAHR, 2007).

2.3.5 Cation Exchange Capacity (CEC)

Biochar usually features a high CEC, thus when applied to soil it will add negative charge. Once biochar is incorporated into soil CEC varies depending on soil pH, age and weathering conditions of biochar (Major et al., 2009). Lee et al. (2010) confirm that CEC is dependent on pH by observing that, at pH values below 7, acidification leads to release of bound cations.

Moreover, CEC in soil might increase over time due to oxidation, thus aged biochar shows increased retention capacity when compared to fresh biochar (Cheng et al., 2008). Cheng & Lehmann (2009), Hale et al. (2011) and Lin et al. (2012) confirm that ageing of biochar is an important factor concerning interactions of biochar with soil and increase of sorption sites.

Biochar's CEC plays an important role in regard of nutrient retention and plant availability especially for infertile sandy soils common in smallholder farming systems in sub-Saharan Africa (Gwenzi et al., 2015). Lehmann et al. (2003) confirms that an increase in CEC leads to improved retention of nutrients and prevents leaching. Consequently, fertiliser use efficiency could increase.

The high CEC in biochar might also enhance soil aggregation through organic matter and minerals forming complexes with each other and with biochar, similar to clay (Cheng et al., 2006).

The findings in the literature are not consistent. For example, Novak et al. (2009a) found no significant increase in CEC after the application of biochar in soil. In the short-term probably only low-temperature biochar leads to an increase in CEC and enhanced soil fertility (Novak et al. 2009a). In a study with 17 different types of biochar incubated with a fine loamy soil Brewer et al. (2011) found no significant change in CEC and no link between feedstock or production conditions with CEC in soil due to a short incubation time (8 weeks). This suggests that only longer interaction times of soil with biochar might lead to beneficial effects (Mukherjee & Lal, 2014).

2.4 Effects of Biochar on Crop Productivity

The main reasons for increased crop productivity following biochar application can be divided into the following (Sohi et al., 2009; Hossain et al., 2010; Jeffery et al., 2011; Sukartono et al, 2011; Lehmann et al., 2003; Major et al., 2010b):

i. direct alteration of soil chemistry through biochar's inherent characteristics including liming effect in acidic soils, direct nutrient addition through biochar, overall higher nutrient availability and nutrient use efficiency

ii. allocation of chemically active surfaces that influence the dynamics of soil nutrients

iii. modification of physical soil properties that leads to increased root growth and/or water and nutrient retention and plant availability.

In this context (i) might cause changes in crop productivity only on a temporary basis and the extent and longevity of the change in crop productivity is for example dependent on biochar weathering. Weathering of biochar takes place when biochar is subjected to precipitation, temperature variations, ice and/or deposition of atmospheric chemicals (IBI, 2012).The effects of (ii) and (iii) are based on biochar's long-term physical persistence (Sohi et al., 2009). Gaskin et al. (2010) and Major et al. (2010b) state that biochar addition to soil might cause an initial negative crop response but due to ageing lead to improvements in plant yield in the long term.

According to McClellan et al. (2007), the cases where biochar leads to decreasing plant growth can be linked to short-term high pH levels, volatile or mobile matter and nutrient imbalance of fresh biochar. Although biochar with an initial alkaline pH value is suitable as an amendment for acidic, degraded soil, it might lead to nutrient deficiencies in plants, when soil gets too alkaline (Hunt et al. 2010; Kishimoto & Sugiura 1985; McElligott et al. 2011; Xu et al. 2012).

Biochar amendment on different soils has led to increased availability and uptake of nutrients by plants (Hass et al., 2012; Uzoma et al., 2011). In their study, Alburquerque et al. (2013) observed that biochar with higher ash content lead to relatively higher increase in sunflower growth due to increased plant availability of nutrients. Moreover, when addition of biochar directly reduces a certain soil constraint increase in crop productivity is a likely outcome. For example, the use of biochar with high mineral content is advisable for soils dependent on high nutrient inputs or soils showing low physical fertility (Slavich et al., 2013).

The positive effects of biochar application on plant growth - for example due to retention of nutrients - are strongest when combined with organic or inorganic fertilisers, especially on tropical soils (Alburquerque et al., 2013; Glaser et al., 2002; Hossain et al., 2010; Schulz & Glaser, 2012; Van Zwieten et al., 2010b; Ogawa et al., 2006; Woolf, 2008). Peng et al. (2011) found an increase in maize biomass by 64% (without NPK fertiliser) and an increase of maize biomass by 146% (with NPK fertiliser) for an Ultisol following biochar application (2.4 t ha^{-1}).

Regarding application rate Glaser et al. (2001) and Ogawa et al. (2006) observed that the addition of low amounts of biochar (0.5 t ha^{-1}) had notable effects on various plant species whereas higher doses of biochar appeared to limit plant growth.

Alburquerque et al. (2014) found a high dependence of plant growth responses upon biochar type in their study. Application of biochar based on nutrient-poor feedstock might have limited effects regarding nutrient availability and thus soil fertility in soil in the short term (Alburquerque et al., 2014). On the contrary, Torres (2011) found that biochar based on nutrient-poor maize cobs had significant effects on crop growth, whereas biochar based on a nutrient-rich feedstock did not. Kimetu et al. (2008) observed a doubled maize yield compared to control on a degraded heavy (45-49% clay) and light (11-14% clay) Ultisol amended with wood biochar during a field study in West Kenya.

These findings indicate that effects of biochar application on crop yield are complex and rest on various factors like application rate, biochar properties, soil properties, limitations, crop responses and management practice. Crop response can be either positive or negative (Chan & Xu, 2009; Jeffery et al.; 2011; Schulz & Glaser, 2012; Mukherjee & Lal, 2014).

2.5 Effects of Biochar dependent on Soil Type

Nitisol is a deep, well-drained, red soil with diffuse horizon boundaries in tropical regions. The subsurface horizon contains at least 30 percent clay and is considered to be fertile, although it is strongly weathered and shows low levels of available P and usually a low base status. P-fixation is notable, but acute P-deficiency occurs rarely. Nevertheless, the application of P-fertiliser is recommended. Nitisols features a nitic horizon, which is a clay-rich subsurface horizon, starting within 100 cm from the soil surface (ISRIC, 2015). Nitisols usually have a clay-dominated texture (Deckers et al., 1998). The soil water retention of Nitisol is fair, as it only retains about 5-15 percent per volume plant-available moisture. The rootable soil layer stretches to great depth, usually deeper than 2 m to compensate for the limited waterholding capacity. Nitisols have a high CEC compared to other tropical soils and the soil pH ranges between 5 and 6.5. (ISRIC, 2015).

Regarding soil nutrients, when clayey soil is amended with biochar it is uncertain whether there is a competition for sorption sites between clay surfaces and biochar and whether lower application rates of biochar are suitable in this case (Mukherjee & Lal, 2014).

The different pore sizes in soil are micropores (5 to 30 µm), mesopores (30 to 75 µm) and macropores (>75 µm) (Soil Science Society of America, 1997). Mesopores are desirable concerning water balance in soil, since they enable water to move according to matric potential differences, for example from saturated to non-saturated areas. Micropores keep water in place and macropores might lead to fast movement of water through soil (Major, 2009).

Biochar’s actual effect on soil moisture is among other things related to changes in pore-size distribution following application (Mukherjee & Lal, 2014). When considering that biochar’s pore size is rather constant and pore size of mineral soil is dependent on texture it can be assumed that biochar application increases available soil moisture in sandy soils, is neutral towards soil moisture in medium textured soil and decreases available soil moisture in clayey soil (Sohi et al., 2009). Pursuant to that, biochar is assumed to increase water holding capacity and crop water supply especially for infertile sandy soils and dry environments, which are common in smallholder farming systems in sub-Saharan Africa (Atkinson et al., 2010; Blackwell et al., 2010; Gwenzi et al., 2015). The small specific surface area of sandy soils is the reason for its low capacity to store water and retain plant nutrients (Troeh & Thompson, 2005).

In addition, Tyron (1948) observed an increase in water content in sandy soils when amended with biochar, whereas the effect could be contrary in clayey soil. Since water is held stronger in smaller pores, clayey soil already shows high water retention (Krull et al., 2004), thus there might be less potential for further improvement through addition of biochar. Moreover, biochar's potential hydrophobicity might also influence actual soil moisture (Mukherjee & Lal, 2014; Tyron, 1948).

The following table shows effects of charcoal on available moisture in soil (in %) dependent on soil texture, as observed by Tyron (1948). An increase in available moisture was found in sandy soil only, whereas there was no change in loamy soil and even a decrease in available moisture in clayey soil following charcoal addition.

Table 2: Effect of charcoal on available moisture [%] depending on soil texture on a volume basis (Tyron, 1948).

Soil Texture	0% Charcoal	15% Charcoal	30% Charcoal	45% Charcoal
Sand	6.7	7.1	7.5	7.9
Loam	10.6	10.6	10.6	10.6
Clay	17.8	16.6	15.4	14.2

2.6 Effects of Biochar dependent on Biochar Type (Maize and Coffee)

The actual effects of biochar on soil are dependent on the soil type and the plant species grown on the area of application (Downie, 2011), as well as biochar type and application rate (Alburquerque et al., 2014; Atkinson et al., 2010; Laird et al., 2010). Nutrient concentration and production conditions of biochar might have a considerable impact on plant growth (Lehmann & Joseph, 2009).

Amongst other factors, the type of biochar should be chosen based on its effects on soil nutrient availability in the particular agricultural soil where it is planned to be applied (Alburquerque et al., 2014). Biochar based on animal biomass or manures features a higher pH than biochar based on plant biomass (Novak et al., 2009b; Singh et al., 2010; Spokas et al., 2011). Singh et al. (2010) found that animal manure feedstocks produced biochar with higher nutrient content compared to plant feedstocks due to the initially higher nutrient content in animal manure.

Lei & Zhang (2013) found that soil amended with plant-based biochar, in particular woodchips, showed a higher water content the same suction than soil amended with dairy manure biochars.

For biochar produced from maize stover, Rajkovich (2010) only found a small yield increase, despite a rather narrow C/N ratio, while Torres (2011) observed significant effects on crop growth for biochar based on maize cobs. Herath et al. (2013) found no improvements in available water holding capacity in silt loam soils amended with maize stover biochar produced at 350 and 550°C applied at a high rate (up to 11.3 t ha^{-1}) after 295 days of incubation, since micropores had been blocked by ash or the mineral fraction over time.

In their study, Deal et al. (2011) investigated the potential of different plant-derived biochars as a soil amendment in the humid tropics. The greatest maize growth was found for coffee husk biochar when compared to other biochars, including maize cob biochar.

In Table 3 properties of maize cob and coffee husk biochar produced in a kiln at 400 to 800 °C (Deal et al., 2011) and 500 °C (Dume et al., 2015) respectively are shown.

Table 3: Physicochemical properties of biochar produced from maize cob and coffee husk.

Parameters	Maize cob	Coffee husk
Moisture (g kg^{-1}) * [a]	31	60
Volatiles (g kg^{-1}) ** [a]	170	233
Fixed C (g kg^{-1}) ** [a]	629	606
Ash (g kg^{-1}) ** [a]	138	160
Specific surface area (m^2 g^{-1}) [b]	4.46	26.20
pH-H_2O (1:10) [b]	8.15	11.04
Exchangeable K (me/100 g) [b]	1.71	2.77
CEC (me/100 g) [b]	47.52	79.23
Organic Carbon (%) [b]	13.98	26.91
Organic Matter (%) [b]	24.09	46.39
Total N (%) [b]	1.20	2.32
Available P (mg kg^{-1}) [b]	8.55	13.87

*reported on a wet basis, **reported on a dry basis

a. Deal et al. (2011)

b. Dume et al. (2015)

3 Materials and Methods

The methods used in this thesis are divided into three separate parts: 1) fieldwork, 2) NIR scanning and 3) laboratory work. The fieldwork was carried out during a month in June 2015. The two farms visited are located in two different areas in Kenya, one is located in Siaya in Western Kenya and one in Embu in Eastern Kenya.

3.1 Fieldwork

3.1.1 Experimental Setup

3.1.1.1 Farming Practices

The two farms investigated feature the same management practices for the last 2-3 cropping seasons. In each farm, there is no use of organic or inorganic fertiliser, pesticides and irrigation. The main crop grown in both farms is maize. *Striga* (witch-weed) is a problem in Siaya (IITA & SLU, 2015).

3.1.1.2 Processing and Application of Biochar within the Experiment

The feedstock used for producing biochar is maize cobs and maize stover in Siaya and coffee husk in Embu. The feedstock for production was collected in Nyabeda, Siaya County and Kibugu, Embu County, then dried and transported to Maseno for charring. Each feedstock was produced separately and care was taken in order to avoid any contamination of biochar. In order to achieve the same particle size as that of the soil the biochar was ground to small granules. Biochar was applied and incorporated in soil in Siaya on the 9th of April and in Embu on the 17th of April (IITA & SLU, 2015).

3.1.1.3 Treatments within the Experiment

The eight treatments within the experiment were arranged in a randomised complete block design (RCBD) and replicated 3 times. Di-ammonium phosphate (DAP) was used as fertiliser. Biochar was applied in furrows and was incorporated manually to a soil depth of 0-15 cm. The crop planted in the experiments was maize. It was improved hybrid maize varieties, DH04 in Siaya and H513 in Embu. The maize was planted at a spacing of 75 cm between the rows and 25 cm within the rows in

March/April and was harvested in August/September 2015. The fertiliser was applied along the furrows and care was taken in order to avoid ‘fertiliser burn’ of the maize seeds. (IITA & SLU, 2015).

The application rates of biochar and fertiliser can be seen in Table 4.

Table 4: Amount of biochar and fertiliser in kilograms applied per sub-plot (IITA & SLU, 2015*).*

Region	Sub-plot Size (m)	Sub-plot area (m^2)	Treatment	Biochar application rates ($t\ ha^{-1}$)	Amount of biochar per sub-plot (kgs)	Amount of DAP per subplot (kgs)
Western Kenya (Siaya)	5x4	20	Control (no inputs)	0	0	0
			DAP	0	0	0.67
			1 ton/ha biochar	1	2	0
			1 ton/ha biochar + DAP	1	2	0.67
			5 ton/ha biochar	5	10	0
			5 ton/ha biochar + DAP	5	10	0.67
			10 ton/ha biochar	10	20	0
			10 ton/ha biochar+DAP	10	20	0.67
Central Kenya (Embu)	4x3	12	Control (no inputs)	0	0	0
			DAP	0	0	0.4
			1 ton/ha biochar	1	1.2	0
			1 ton/ha biochar + DAP	1	1.2	0.4
			5 ton/ha biochar	5	6	0
			5 ton/ha biochar + DAP	5	6	0.4
			10 ton/ha biochar	10	12	0
			10 ton/ha biochar+DAP	10	12	0.4

3.1.2 Sampling Layout and Collection of Soil Samples

In Siaya, the total size of a main plot is 44.5 x 14 meters, while the sub plot size is 5 x 4 meters with 0.5 meter path between each treatment and replicates and blocks. The layout of a plot and corresponding sampling points can be seen in Figure 3. There are 6 planting rows along length in each sub plot. Samples have only been taken within the net plot, which is shown as a black rectangle in Figure 3.

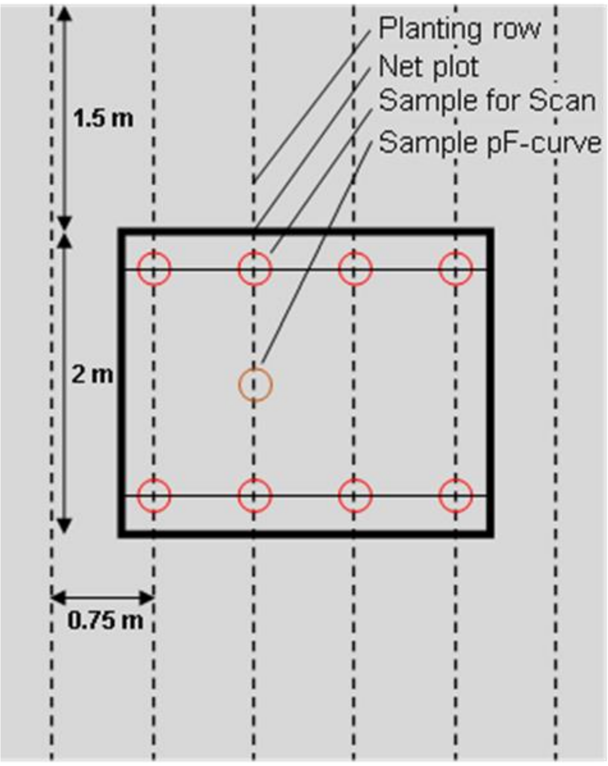

Figure 3: Layout of plots and sampling points in Siaya.

In Embu, the total size of a main plot is 36.5 x 11 meters, while the sub plot size is 4 x 3 meters with 0.5 meter path between each treatment and replicate/blocks. The layout of a plot and corresponding sampling points is shown in Figure 4. The number of planting rows and size of the net plot in the plots equals the one in Siaya. As for Siaya, samples were only taken in the net plot.

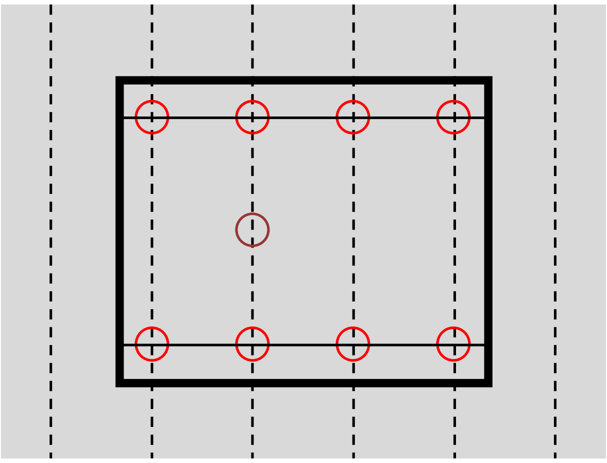

Figure 4: Layout of plots and sampling points in Embu.

Each sub plot featuring a different treatment is replicated 3 times, for a total of 24 sub plots per site. The plots were subject to crop management practices including weed control and soil tillage methods.

Until the first day of soil sampling biochar has been in soil for 69 days in Siaya and 70 days in Embu. Maize plants on both sites were growing for 2-3 months until then.

Soil samples for determining the soil moisture and bulk density were collected from 17th to 19th of June at one farm in Siaya and from 26th to 28th of June at one farm in Embu. During these 3 days per site, each day 8 treatments/sub plots belonging to one block/replicate were sampled.

Soil samples for determining soil water retentions were collected on the 20th of June in Siaya and on the 29th of June in Embu.

For carrying out the scans with the NIR spectrometer 8 soil samples of each of the 24 sub plot were taken. Out of the 8 samples per sub plot 25%, which equals 2 samples per sub plot, were chosen randomly for determining the soil moisture in the laboratory. The samples were collected with a cylinder of 48 mm diameter at 0-10 cm depth, put in a plastic bag and homogenised manually as effectively as possible.

Soil samples for determining the soil water retention (pF-curve) were taken separately from the other samples, as can be seen in Figure 3 and Figure 4. Since soil water retention is assumingly not affected by fertiliser the samples for determining the pF-curve were only taken in plots with no added fertiliser. Only one sample per sub plot with no fertiliser addition, 12 samples per site, 24 samples in total for both sites, were taken and were analysed for soil water retention in the soil hydrological laboratory at the Department of Soil and Environment at SLU in Uppsala. The samples were collected with a cylinder to a depth of 10 cm and kept undisturbed. On both ends of the cylinders, a filter paper was placed, and then they were closed with a lid and wrapped in plastic foil.

3.2 NIR Scanning

The visible near infrared (VNIR) radiation refers to the electromagnetic spectrum between 400 and 2500 nm (Cañasveras et al., 2012). In this spectrum, most organic and some inorganic compounds exhibit distinguished reflectance or transmittance properties (Wang et al., 2004). VNIR spectroscopy works through the tendency of molecules to absorb light in VNIR's electromagnetic spectrum (Stenberg et al., 2010). A material's or compound's spectral signature – pattern of electromagnetic radiation referring to the material or compound – is identified by their reflectance or absorbance dependent on wavelength (Brown et al., 2006).

The use of NIR spectroscopy is a fast, non-destructive and non-invasive analytical method exhibiting a high penetration depth of the probing radar beam. Moreover, it allows in-line use and almost universal application, while requiring only minimum sample preparation (Pasquini, 2003).

Soil and maize leaf spectra were taken by using FieldSpec4 Standard-Res Spectroradiometer (Analytical Spectral Devices, Boulder, CO, USA) with a high intensity contact probe for soil and a plant probe with leaf clip for maize leaves. Samples were scanned at 1.4 nm intervals in the wavelength range between 350 and 1000 nm and at 1.1 nm intervals in the wavelength range between 1001 and 2500 nm.

Per site, 192 soil samples, in total 384 for both sites, were scanned with the VNIR spectroradiometer at 3 different points each. Spectra of soil samples were taken on the same day as the respective soil samples were collected. Thus, spectra for determining the soil moisture were taken from 17th to 19th of June in Siaya and from 26th to 28th of June in Embu. During these 3 days per site, each day the spectra of 8 treatments belonging to one block were taken.

Spectra of maize leaves for determining macronutrient content were taken on the 20th of June in Siaya and on the 29th of June in Embu. For maize plants, the most recently developed leaf of the maize plants closest to the randomly selected soil sample points (2 out of 8 in total per sub plot) was scanned in its middle. This equals 48 measurements (2 samples x 24 sub plots) in per site, 96 measurements in total.

3.3 Laboratory Work

3.3.1 Soil Moisture and Bulk Density

In order to determine soil moisture and bulk density 25 % of the samples taken each in Siaya and Embu for that purpose, in total 96, were weighed when fresh and after oven drying at 105°C for 24 hours in a laboratory at ICIPE campus in Nairobi, Kenya.

Soil moisture on wet weight basis (W_m) was preferred over soil moisture on dry weight basis (W_d). For W_d the values can range from 0 (no water present) to infinity (only water present), thus a given increase of water in soil is not parallel to an increase of dry weight. By comparison, W_m has a fixed range from 0 (no water present) to 100 (only water present), thus the values represent the actual weight of water in each 100 g of soil. Related to statistical analysis, values obtained from W_d may be unsuitable for statistical analysis, at least without transformation, in respect of normality. This is related to the fact that variance between samples changes with changes in water content. For W_m a constant variance between several groups or for a whole dataset and normal distribution of values is more likely found (Robinson, 1974).

Gravimetric soil water concentration on wet weight basis (W_m) was calculated by subtracting mass of dry soil from mass of wet soil and dividing the obtained water content by the mass of wet soil.

$$\boldsymbol{W_m} = \frac{\boldsymbol{M_w} - \boldsymbol{M_d}}{\boldsymbol{M_w}}$$

Equation 1: Calculation of gravimetric soil water concentration on wet weight basis. M_d is the mass of dry soil and M_w is the mass of wet soil. (Based on Vogt et al. (2015)).

Bulk density (P_b) was calculated by dividing dry soil weight by the total volume of cylinders used.

$$p_b = \frac{M_d}{V_t}$$

Equation 2: Calculation of dry bulk density. M_d is the mass of dry soil and V_t is total volume of the soil sample. (Based on Vogt et al. (2015)).

3.3.2 Soil Water Retention

In order to determine soil water retention 12 samples taken each in Siaya and Embu, in total 24, were analysed to determine water-holding capacity. Water content in vol-% at different soil water tensions was determined.

The pF values 1.7, 3 and 4.2 (permanent wilting point) were chosen for analysis. These specific suction pressures were chosen in order to cover an as large as possible range of water contents, and as a result increase the likelihood to find significant differences for biochar rates. Literature on soil water retention in Nitisol for different horizons (Karuku et al., 2012) was consulted and based on a soil water retention curve for an AP soil horizon (0-25 cm) pF of 1.7 was chosen, since water content for Nitisol was rather stable until this suction pressure and started to change from there. The pF of 3 was chosen, since up that suction soil water is considered to be readily plant available (Landon, 2014) and pF of 4.2 was chosen since it refers to the permanent wilting point.

The pF of 1.7 was assumed to approximate field capacity. Based on that approximate available water capacity (θ_a) was calculated by substracting water content at permant wilting point from water content at field capacity.

$$\theta a = \theta_{fc} - \theta_{pwp}$$

Equation 3: Calculation of approximate available water capacity. θ_{fc} is the water content at field capacity and θ_{pwp} is the water content at permanent wilting point. (Based on Veihmeyer & Hendrickson (1927)).

3.4 Development of NIR Calibrations and Analysis of Spectra

Spectral data were processed using The Unscrambler software (Camo Software, Oslo, Norway). As already mentioned, three scans were taken at 90° angle of each soil sample. The resulting three spectra for one soil sample were averaged in the software in order to obtain a single scan for each sample. For the maize leaves one scan per leaf was taken in the middle of each leaf, thus no further processing prior analysis in the software was necessary. The absorbance is measured in log10 1/R, where R is reflectance. Within the modelling of the data obtained through spectral scanning Partial Least Square Regression, which uses the first derivative of soil reflectance, is applied in order to reduce high-dimensional spectral data derived from NIR detectors (Brown et al., 2006).

The obtained data on gravimetric soil water concentration (96 oven-dried samples) was further used as predictor variables within the model calibration in The Unscrambler in order to predict soil moisture for all spectra of the scanned samples.

For predicting nutrient properties of maize leaves already existing PLS regression models were used.

Within the PLS regression in The Unscrambler the correlations of predictor variables and response variables in the created calibration model were expressed as R-square values. R-square indicates the percentage of variation of the response variable that is explained by its relation with one or more predictor variables. In Table 5 the R-square values for the calibration models can be seen.

Table 5: R-square of analysed properties in The Unscrambler.

Property	R-square
Soil Moisture Siaya	0.96
Soil Moisture Embu	0.91
N content of Maize Leaves	0.75
K content of Maize Leaves	0.49
P content of Maize Leaves	0.60
S content of Maize Leaves	0.69
Moisture content of Maize Leaves	0.92

3.5 Statistical Analysis

For all data, the statistical analysis was performed in JMP. A two-way ANOVA with blocks as random effect was conducted in order to determine significant differences between the biochar application rates and presence or absence of fertiliser regarding soil moisture, bulk density, macronutrient (N, P, K, S) and moisture content of maize leaves in field. A one-way ANOVA was conducted in order to determine significant differences between biochar application rates regarding water content at different pF values and macronutrient (N, P, K, S) content of maize leaves in field for plots amended with fertiliser and plots with no added fertiliser separately.

In case significant differences were found related to biochar rates, the Tukey HSD test was used for post-hoc comparison. For significant differences related to presence or absence of fertiliser, the Least Square Means Differences Student’s t-test was used for post-hoc comparison.

Prior to analysis the respective data was checked for the assumptions of normality and homogeneity of variances. For data, that did not fullfill the assumptions all non-parametric tests available in JMP were applied to.

4 Results

4.1 Soil Moisture

SIAYA

There was a significant effect of the biochar rates [$F(3) = 4.60$, $p = 0.0040$] and presence of fertiliser [$F(1) = 5.88$, $p = 0.0163$] at the $p < .05$ level.

Table 6: Analysis of variances - Soil moisture in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	4.60	0.0040*
DAP	1	5.88	0.0163*
Biochar/DAP	3	1.41	0.2438

*indicates a significant statistical difference with p < .05

Table 7 shows that the mean scores of the biochar rate of 10 t ha^{-1}and the biochar rate of 5 t ha^{-1}were significantly different from control (biochar rate of 0 t ha^{-1}). In addition, the mean score of the biochar rate of 1 t ha^{-1} is noticeably higher than the mean score of the control treatment.

Table 7: Post-hoc comparison using Tukey HSD test - Soil moisture in Siaya.

Rate	N	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
10	48	23.6 A	1.10	0.16	23.2	23.9
5	48	23.4 A	1.06	0.15	23.1	23.7
1	48	23.3 A B	0.88	0.13	23.1	23.6
0	48	22.9 B	0.90	0.13	22.6	23.1

Regarding fertiliser, the mean score ($M = 23.47$) of presence of fertiliser was significantly different from the mean score ($M = 23.12$) for absence of fertiliser.

EMBU

In contrast to Siaya, there was no significant effect of the biochar rates but also an effect of the presence of fertiliser [$F(1) = 68.21$, $p < 0.0001$] at the $p < .05$ level.

Table 8: Analysis of variances - Soil moisture in Embu.

Source	DF	F Ratio	Significance
Biochar	3	0.48	0.6978
DAP	1	68.21	<.0001*
Biochar/DAP	3	2.40	0.0695

*indicates a significant statistical difference with p < .05

For fertiliser, the mean score ($M = 22.47$) of presence of fertiliser and the mean score ($M = 21.08$) of absence of fertiliser were significantly different.

In Figure 5, the mean scores for soil moisture dependent on biochar rates are illustrated.

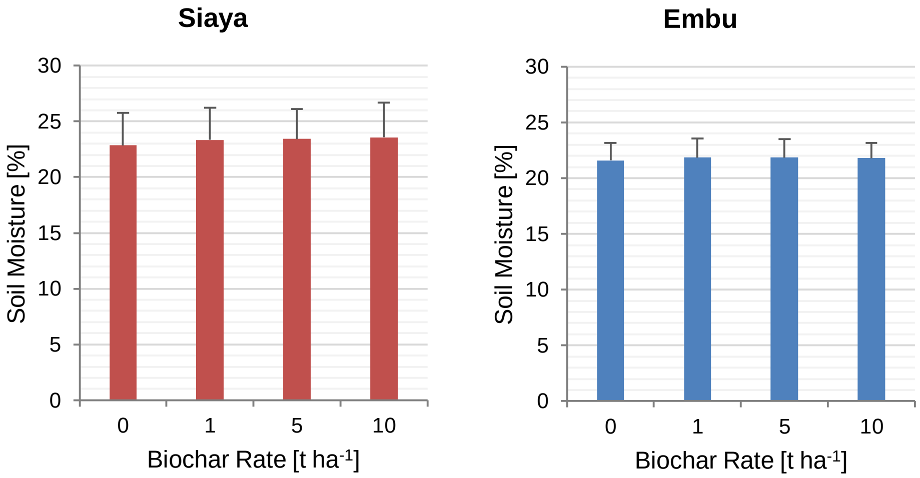

Figure 5: Soil moisture [%] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviation.

4.2 Soil Water Retention

SIAYA

There was no significant effect of the biochar rates at any of the pF values at the $p < .05$ level.

Table 9: Analysis of variances - Soil water retention in Siaya.

Source	DF	F Ratio	Significance
Biochar Rate at pF 1.7	3	2.60	0.1241
Biochar Rate at pF 3	3	1.74	0.2366
Biochar Rate at pF 4.2	3	3.46	0.3751

As can be seen in Table 10, despite a lack of significant differences, there is a notable difference in soil moisture for control soil samples compared to soil samples, which received biochar treatment for the pF values 1.7 and 3. Based on water content at pF of 1.7 and water content at pF of 4.2 approximate available water capacity was calculated.

Table 10: Soil water retention at different pF values and approximate available water capacity dependent on biochar rate in Siaya.

Rate	N	Mean for pF 1.7	Mean for pF 3	Mean for pF 4.2	AWC (%)
10	3	41.8	33.2	25.7	16.1
5	3	42.4	34.3	28.0	14.4
1	3	42.1	34.3	26.1	16.0
0	3	37.9	30.9	25.7	12.2

In Figure 6, a soil water retention curve based on soil moisture at different pF values and depending on biochar rates is illustrated.

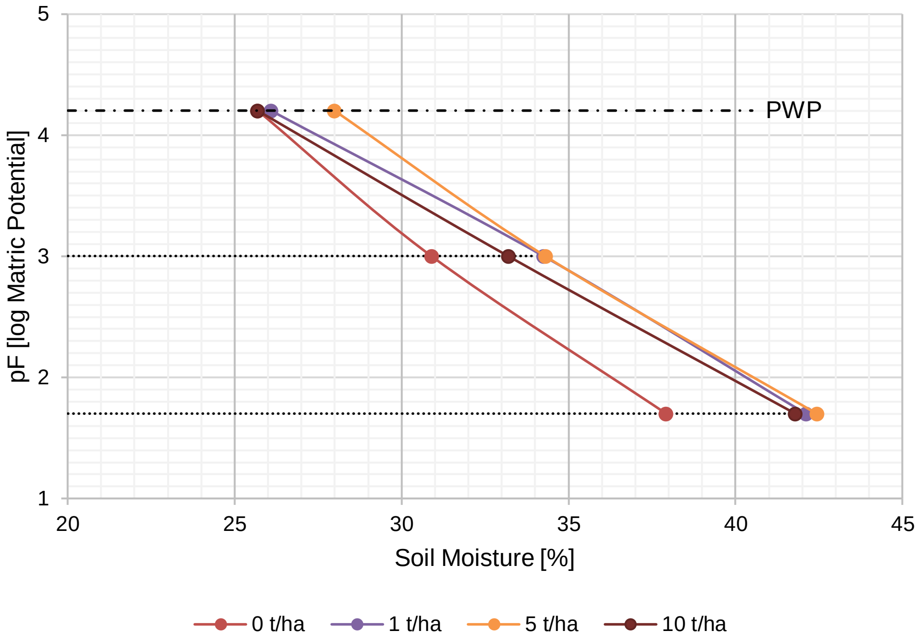

Figure 6: Soil water retention curve of Siaya. Soil Moisture [%] dependent on pF value [log Matric Potential] and biochar rate [t ha^{-1}]. PWP = Permanent wilting point.

In Figure 7, soil moisture at different pF values and depending on different biochar rates is illustrated, including standard deviations.

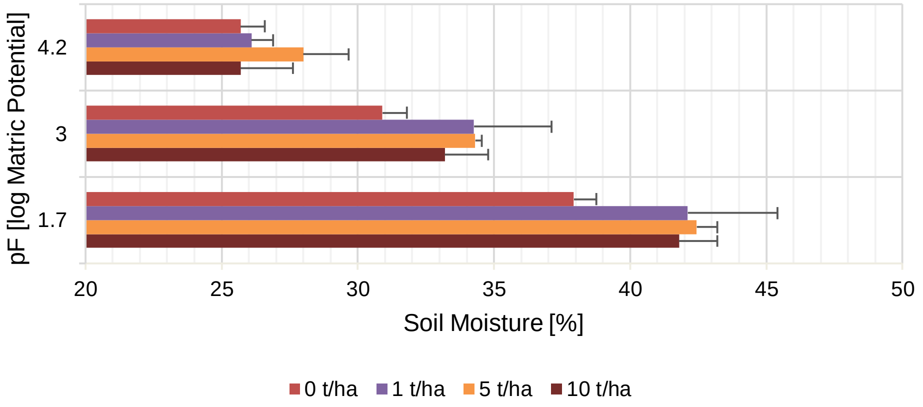

Figure 7: Soil moisture [%] dependent on biochar rate [t ha^{-1}] and pF value in Siaya. Error bars represent standard deviation.

EMBU

In Embu, there was no significant effect of the biochar rates at any of the pF values, at the $p < .05$ level. In contrast to Siaya, no notable difference in soil moisture at any of the pF values for control soil samples compared to soil samples with added biochar was found, as can be seen in Figure 8.

Table 11: Analysis of variances - Soil water retention in Embu.

Source	DF	F Ratio	Significance
Biochar Rate at pF 1.7	3	0.13	0.9407
Biochar Rate at pF 3	3	0.29	0.8347
Biochar Rate at pF 4.2	3	2.11	0.1768

In contrast to Siaya, there is no notable difference in soil moisture for control soil samples compared to soil samples, which received biochar treatment. Also for approximate available water capacity, no significant differences were found.

Table 12: Soil water retention at different pF values and approximate available water capacity dependent on biochar rate in Embu.

Rate	N	Mean for pF 1.7	Mean for pF 3	Mean for pF 4.2	AWC (%)
10	3	40.5	26.4	21.1	19.4
5	3	41.1	26.6	21.0	20.1
1	3	40.7	26.1	22.1	18.6
0	3	40.6	26.0	21.8	18.8

In Figure 8, a soil water retention curve based on soil moisture at different pF values and dependent on different biochar rates is illustrated.

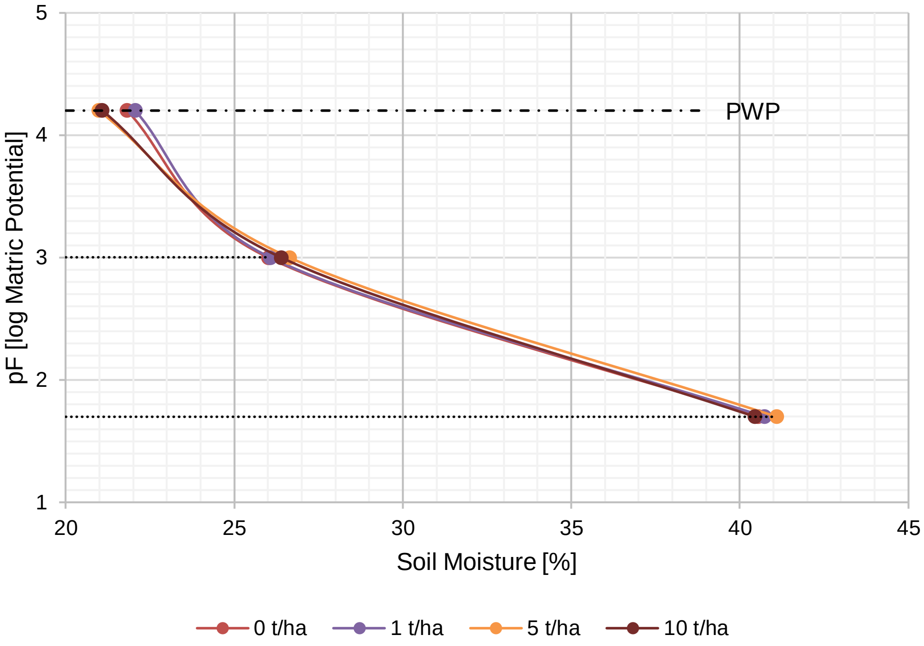

Figure 8: Soil water retention curve of Embu. Soil moisture [%] dependent on pF value [log Matric Potential] and biochar rate [t ha^{-1}]. PWP = Permanent wilting point.

In Figure 9, soil moisture at different pF values and at different biochar rates is illustrated, including standard deviations.

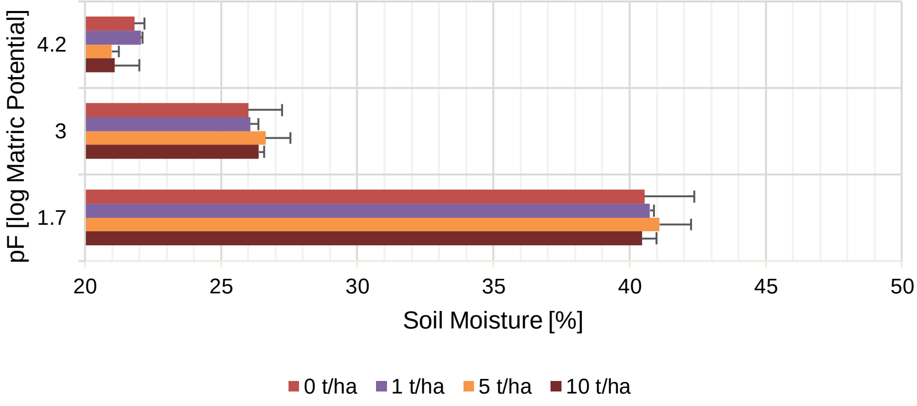

Figure 9: Soil moisture [%] dependent on biochar rate [t ha^{-1}] and pF value in Embu. Error bars represent standard deviation.

4.3 Bulk Density

SIAYA

There was a significant effect of the biochar rates [$F(3) = 3$, $p = 0.0424$] but no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 13: Analysis of variances - Bulk density in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	3.00	0.0424*
DAP	1	4.09	0.0502
Biochar/DAP	3	1.99	0.1326

*indicates a significant statistical difference with p < .05

Despite a significance for biochar rate in Table 13, post-hoc comparison using the Tukey HSD test found no significant differences between biochar rates.

EMBU

As for Siaya, there was a significant effect of the biochar rates [$F(3) = 4.11$, $p = 0.0128$] but no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 14: Analysis of variances - Bulk density in Embu.

Source	DF	F Ratio	Significance
Biochar	3	4.11	0.0128*
DAP	1	2.45	0.1256
Biochar/DAP	3	1.47	0.2369

*indicates a significant statistical difference with p < .05

As can be seen in Table 15, the mean score of the biochar rate of 1 t ha^{-1} is significantly different from the biochar rate of 5 t ha^{-1}. Soil samples that received a biochar rate of 1 t ha^{-1} show the highest bulk density and soil samples that received a biochar rate of 5 t ha^{-1} show the lowest bulk density.

Table 15: Post-hoc comparison using Tukey HSD test – Bulk density in Embu.

Rate	N	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
10	12	0.92 A B	0.08	0.02	0.87	0.98
5	12	0.87 B	0.09	0.03	0.81	0.93
1	12	0.98 A	0.07	0.02	0.94	1.03
0	12	0.96 A B	0.09	0.03	0.90	1.01

In Figure 10, the means scores for bulk density dependent on biochar rates are illustrated.

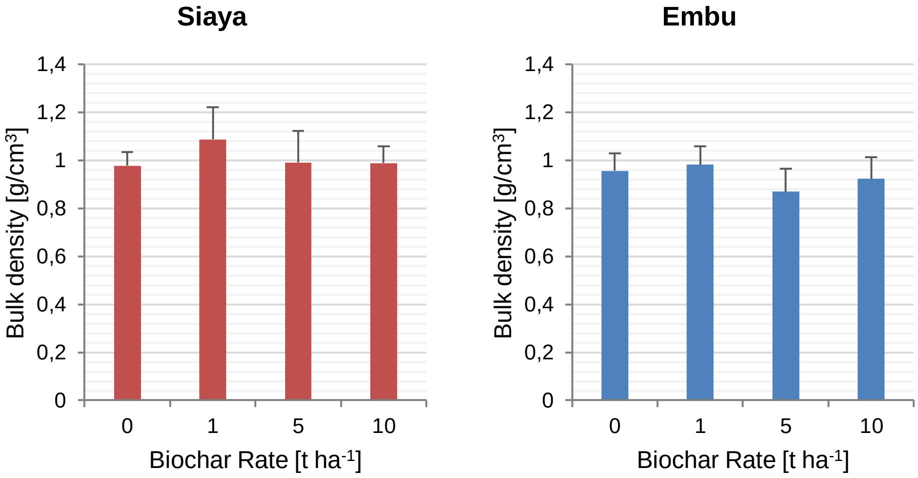

Figure 10: Bulk density [g/cm^3] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviation.

4.4 Nutrient and Moisture Content (MC) of Maize Leaves

4.4.1 Nitrogen

SIAYA

There was no significant effect of the biochar rates but an effect of the presence of fertiliser [$F(1) = 7.37$, $p = 0.0099$] on N content of maize leaves at the $p < .05$ level.

Table 16: Analysis of variances - N content of maize leaves in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	1.46	0.2413
DAP	1	7.37	0.0099*
Biochar/DAP	3	1.62	0.2008

*indicates a significant statistical difference with p < .05

For fertiliser, the mean score ($M = 2.03$) of presence of fertiliser was significantly different from the mean score ($M = 1.82$) of absence of fertiliser.

When only analysing data on plots that received DAP, no significant difference was found for biochar rate. In contrast, for plots that received no DAP significant differences for biochar rate were found (Table 17), but did not follow a trend of increasing N content with biochar rate, as can be seen in Table 18.

Table 17: Analysis of variance - N content of maize leaves dependent on fertiliser in Siaya.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.10	0.9564
No DAP	Biochar	3	7.43	0.0019*

*indicates a significant statistical difference with p < .05

Table 18: Post-hoc comparison using Tukey HSD test – N content of maize leaves in plots with no DAP in Siaya.

Rate	N	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
10	6	2.03 A B	0.18	0.07	1.89	2.17
5	6	1.73 B C	0.16	0.07	1.58	1.87
1	6	1.62 C	0.17	0.07	1.48	1.76
0	6	1.92 A B	0.14	0.06	1.78	2.06

EMBU

In contrast to Siaya, no significant effect of the biochar rates or presence of fertiliser was found at the $p < .05$ level.

Table 19: Analysis of variances - N content of maize leaves in Embu.

Source	DF	F Ratio	Significance
Biochar	3	0.33	0.7972
DAP	1	1.37	0.2495
Biochar/DAP	3	0.45	0.7219

Although no significant difference was found for fertiliser, the mean score (M = 2.02) of presence of fertiliser is higher than the mean score (M = 1.91) for absence of fertiliser.

For both, plots that received DAP and plots that received no DAP no significant difference was found.

Table 20: Analysis of variance - N content of maize leaves dependent on fertiliser in Embu.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.65	0.5938
No DAP	Biochar	3	2.82	0.0680

In Figure 11, the mean scores for N content of maize leaves dependent on biochar rates are illustrated.

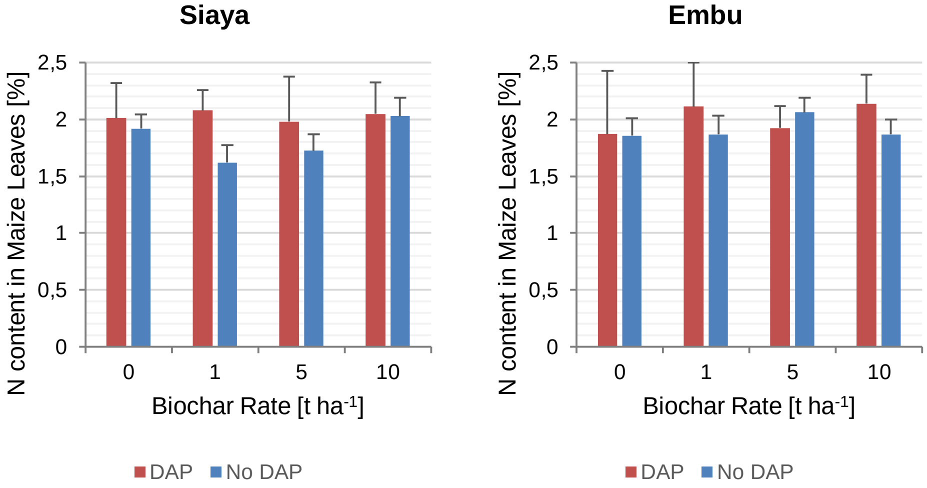

Figure 11: N content of maize leaves [%] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviation.

4.4.2 Phosphorus

SIAYA

There was no significant effect of the biochar rates but an effect of the presence of fertiliser [$F(1) = 18.7$, $p = 0.0001$] at the $p < .05$ level.

Table 21: Analysis of variances - P content of maize leaves in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	0.81	0.4964
DAP	1	18.70	0.0001*
Biochar/DAP	3	1.50	0.2288

*indicates a significant statistical difference with p < .05

The mean score ($M = 1188.62$) of presence of fertiliser and the mean score ($M = 838.38$) for absence of fertiliser were significantly different.

When analysing data on plots that received DAP, separately form plots that received no DAP, no significant differences were found for biochar rate.

Table 22: Analysis of variance - P content of maize leaves dependent on fertiliser in Siaya.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.33	0.8057
No DAP	Biochar	3	2.23	0.1202

EMBU

As for Siaya, there was no significant effect of the biochar rates but an effect of the presence of fertiliser [$F(1) = 4.55$, $p = 0.0394$] at the $p < .05$ level.

Table 23: Analysis of variances - P content of maize leaves in Embu.

Source	DF	F Ratio	Significance
Biochar	3	0.87	0.4643
DAP	1	4.55	0.0394*
Biochar*DAP	3	0.94	0.4321

*indicates a significant statistical difference with p < .05

For fertiliser, the mean score ($M = 1138.78$) of presence of fertiliser was significantly different from the mean scores ($M = 906.55$) for absence of fertiliser.

When data was split into two groups, the first representing samples that did not receive fertiliser and the other one referring to samples that received fertiliser, no significant differences for biochar rates were found for both groups.

Table 24: Analysis of variance - P content of maize leaves dependent on fertiliser in Embu.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.31	0.8153
No DAP	Biochar	3	1.62	0.2205

In Figure 12, the mean scores for P content of maize leaves dependent on biochar rates are illustrated.

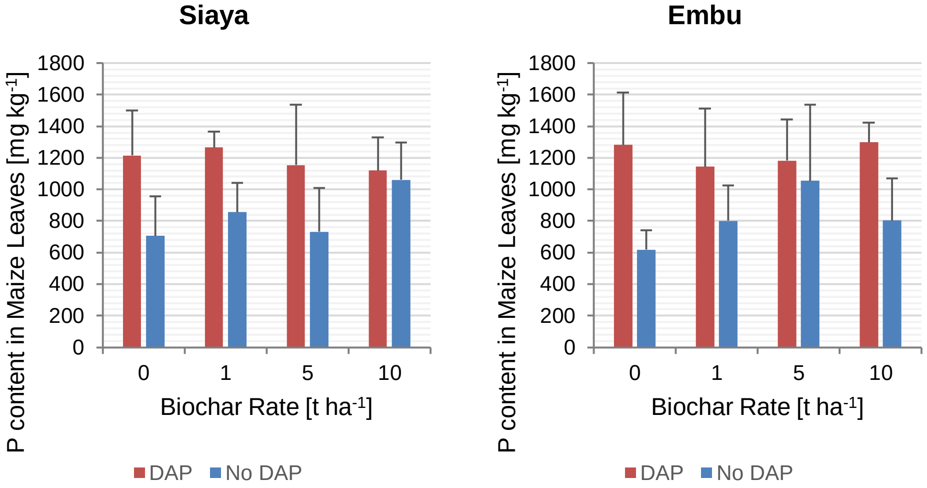

Figure 12: P content of maize leaves [mg kg^{-1}] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviations.

4.4.3 Potassium

SIAYA

The assumption of homogeneity of variances, but not the assumptions of normality is fulfilled for this dataset, thus results of ANOVA cannot be considered robust. There was no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level. In addition, all non-parametric tests offered in the software JMP were conducted and delivered the same results.

Table 25: Analysis of variances - K content of maize leaves in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	0.58	0.6336
DAP	1	3.37	0.0740
Biochar/DAP	3	0.71	0.5528

Although for fertiliser no significant differences in K content of maize leaves could be found, the mean score ($M = 6631.99$) for presence of fertiliser is higher than the mean score ($M = 5690.09$) for absence of fertiliser.

In addition, when analysing data on plots that received DAP, separately form plots that received no DAP, no significant differences were found for biochar rate.

Table 26: Analysis of variance - K content of maize leaves dependent on fertiliser in Siaya.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.32	0.8084
No DAP	Biochar	3	1.78	0.1879

EMBU

As for Siaya, the assumption of homogeneity of variances, but not the assumption of normality is fulfilled, thus results of ANOVA cannot be considered robust. For both ANOVA and the non-parametric tests, no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level was found.

Table 27: Analysis of variances - K content of maize leaves in Embu.

Source	DF	F Ratio	Significance
Biochar	3	0.24	0.8678
DAP	1	0.05	0.8304
Biochar/DAP	3	0.16	0.9248

Despite the lack of significant differences for fertiliser, the mean score (*M* = 7319.40) of presence of fertiliser is higher than the means score for absence (*M* = 7096.15) of fertiliser.

When data on plots that received DAP were analysed separately form plots that received no DAP, no significant differences were found for biochar rate.

Table 28: Analysis of variance - K content of maize leaves dependent on fertiliser in Embu.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.51	0.6790
No DAP	Biochar	3	1.29	0.3093

In Figure 13, the mean scores for K content of maize leaves dependent on biochar rates are illustrated.

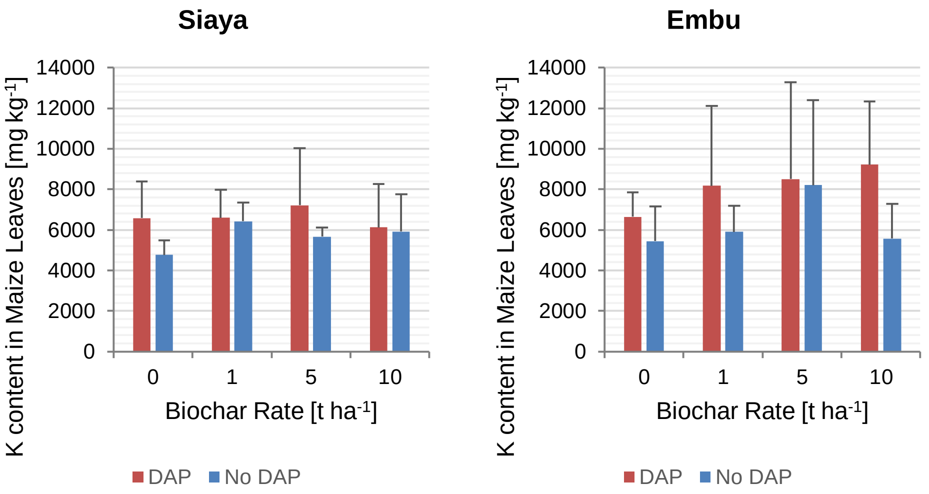

Figure 13: K content of maize leaves [mg kg^{-1}] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviations.

4.4.4 Sulphur

SIAYA

There was no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 29: Analysis of variances - S content of maize leaves in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	2.27	0.0964
DAP	1	0.01	0.9278
Biochar/DAP	3	1.70	0.1827

When only analysing data on plots that received DAP, no significant difference was found for biochar rate. In contrast, for plots that received no DAP significant differences were found (Table 30), but did not follow a trend of increasing S content with biochar rate, as can be seen in Table 31.

Table 30: Analysis of variance - S content of maize leaves dependent on fertiliser in Siaya.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.79	0.5170
No DAP	Biochar	3	7.02	0.0025*

*indicates a significant statistical difference with p < .05

Table 31: Post-hoc comparison using Tukey HSD test – S content of maize leaves in plots with no DAP in Siaya.

Rate	N	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
10	6	2030 A	165	68	1892	2168
5	6	1918 A B	144	59	1780	2056
1	6	1706 B	185	75	1568	1844
0	6	2106 A	124	50	1968	2244

EMBU

The assumption of homogeneity of variances, but not the assumption of normality is fulfilled for this dataset, thus results of Anova cannot be considered robust. Both, ANOVA with blocks as random effect and all non-parametric tests offered in JMP were conducted and found no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 32: Analysis of variances - S content of maize leaves in Embu.

Source	DF	F Ratio	Significance
Biochar	3	1,98	0,1334
DAP	1	0,04	0,8506
Biochar/DAP	3	0,01	0,9981

When data on plots that received DAP were analysed separately form plots that received no DAP, no significant differences were found for biochar rate.

Table 33: Analysis of variance - S content of maize leaves dependent on fertiliser in Embu.

	Source	DF	F Ratio	Significance
DAP	Biochar	3	0.05	0.9833
No DAP	Biochar	3	0.62	0.6096

In Figure 14, the mean scores for S content of maize leaves dependent on biochar rates are illustrated.

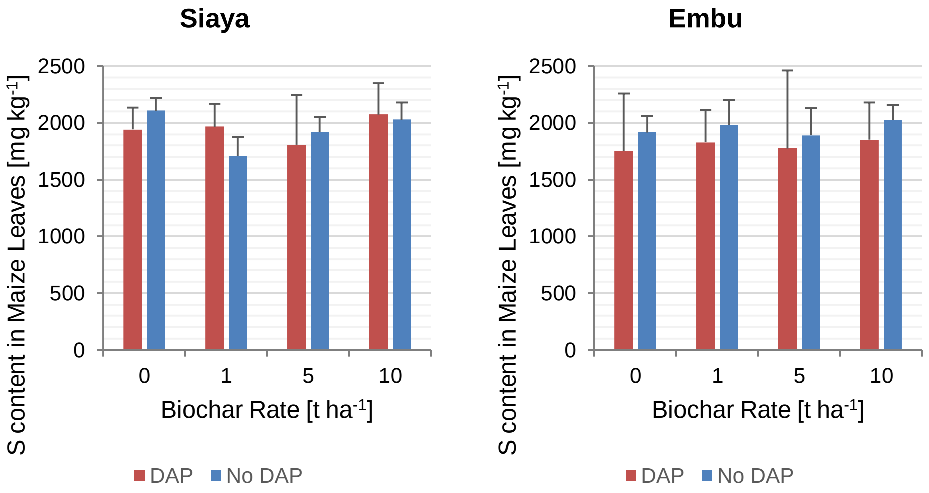

Figure 14: S content of maize leaves [mg kg^{-1}] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars indicate standard deviations.

4.4.5 Moisture Content (MC)

SIAYA

There was no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 34: Analysis of variances - MC of maize leaves in Siaya.

Source	DF	F Ratio	Significance
Biochar	3	1.531	0.2222
DAP	1	0.002	0.9668
Biochar/DAP	3	0.561	0.6442

EMBU

As for Siaya, there was no significant effect of the biochar rates and no significant effect of the presence of fertiliser at the $p < .05$ level.

Table 35: Analysis of variances - MC of maize leaves in Embu.

Source	DF	F Ratio	Significance
Biochar	3	0.34	0.7942
DAP	1	0.12	0.7329
Biochar/DAP	3	1.35	0.2715

In Figure 15, the mean scores and standard deviations for moisture content of maize leaves dependent on biochar rates are illustrated.

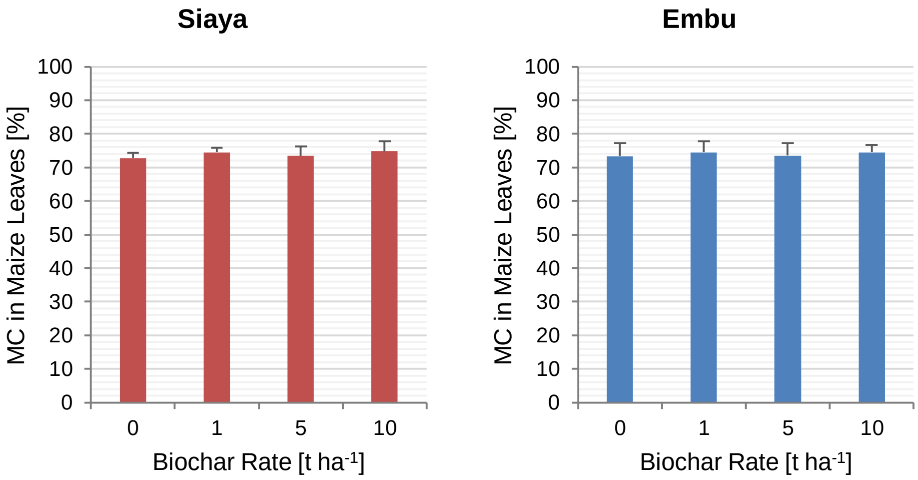

Figure 15: Moisture content of maize leaves [%] dependent on biochar rate [t ha^{-1}] in Siaya and Embu. Error bars represent standard deviations.

5 Discussion

5.1 Limitations of this Study

Since data on soil type and texture, as well as data on biochar properties was not available for the particular sites investigated in Siaya and Embu, data on these properties was taken from the literature. Therefore, information on soil and biochar properties might differ from actual conditions.

A further limitation of this study is the short soil incubation period with biochar. Biochar was applied and incorporated in soil in Siaya on the 9th of April and in Embu on the 17th of April, the soil samples were taken in Siaya from 17th to 20th of June and in Embu from 26th to 29th of June. This results in a soil incubation time of 69 to 72 days for Siaya and a soil incubation time of 70 to 73 days for Embu. That is an issue, since biochar is subjected to oxidation and ageing reactions over time (Brewer et al., 2011). Due to that, the results can only be interpreted as short-term effects of biochar on soil and plant properties.

Moreover, the maize crops were growing 2-3 months until the time of soil sampling and might thus influence results. This is a considerable factor, since the development of the crops varied greatly from one subplot to the other dependent on treatment. Due to that, soil moisture might be influenced by actual plant coverage of respective subplots resulting in varying water availability.

5.2 General findings

5.2.1 Embu vs. Siaya

For field trials conducted at various sites, actual results following biochar applications are highly dependent on the specific site and soil applied to (Mukherjee & Lal, 2014). The difference in results for both sites can also be due to differing properties of the biochar type applied to soil, which is maize cobs and maize stover in Siaya and coffee husk in Embu.

5.2.2 Field Ageing

As already mentioned, biochar has only been subject to a rather short period of soil incubation, 69 to 72 days in Siaya and 70 to 73 days in Embu. Mukherjee & Lal (2014) suggest testing of soil amendment with biochar at field scale for a minimum of two successive seasons. This allows sufficient field ageing of biochar in order to be able to derive robust conclusions on crop yield. While various studies reached the conclusion that crop yields following biochar addition are highly variable, in some cases increases in crop yield were found only several years after application or not at all. Although Major et al. (2010b) indicate that also a single biochar application may offer benefits throughout several cropping seasons, but probably not during the first season following application.

5.2.3 Crop Effects

During the time when soil samples were taken in Siaya and Embu, all of the subplots were planted with maize crops. The development of the maize crops varied greatly from one subplot to another due to effects of fertiliser and possibly effects by biochar rate. Therefore, the results on some investigated properties within this thesis might be influenced to a varying degree by the maize crops planted and their stage of development.

5.2.4 Biochar Rate

Only for one of the investigated properties (Soil moisture in Siaya, Figure 5) an improvement with increasing biochar rate was found. This is contrary to the expectations in Hypotheses 1. For soil water retention in Siaya, at least notable differences between biochar addition and control, although without relation to biochar rate, was found for the two lower water tensions (pF of 1.7 and 3). For the remaining properties, no significant effect of presence of biochar was found.

A lack of statistically significant differences between different biochar rates and the absence of a trend for improvement in investigated properties with increasing biochar rate could be due to the biochar rates. In their study Chan et al. (2008a) detected a statistical difference for many cases only for extremely high biochar rates, namely for rates as high as 50 and 100 t ha^{-1}, but not for a rate of 10 t ha^{-1}.

5.3 Soil Moisture and Soil Water Retention

For Siaya, a slight trend for increasing soil moisture with increasing biochar rate has been found and there was a significant difference in soil moisture for the biochar rate of 10 t ha^{-1} and 5 t ha^{-1} compared to the biochar rate of 0 t ha^{-1}. In addition, the soil moisture for the biochar rate of 1 t ha^{-1} is higher than the soil moisture for the biochar rate of 0 t ha^{-1}, but not at a significant level (Figure 5). For Embu, no significant differences in soil moisture were found (Figure 5). Unexpectedly, a significant difference in soil moisture for presence and absence of fertiliser has been found, for both Siaya and Embu.

For Siaya, notable differences in soil water retention for soil samples with added biochar when compared to control soil samples were found, but not on a significant level. A trend for increasing water content at the pF-values with increasing biochar rate was not found (Figure 6). For Embu, no significant differences for biochar rates in regard to soil water retention were found (Figure 8).

Therefore, hypothesis 1 cannot be falsified for the investigated site in Siaya, but for the investigated site in Embu.

In the following, the results for soil moisture and soil water retention are discussed simultaneously, since the results are quite similar and the same reasons for improvement of investigated properties or lack thereof apply. The statements made in respect to absence or presence of fertiliser only apply for soil moisture, since soil samples for determining soil water retention were only taken in subplots with no added fertiliser.

When it comes to the influence of soil texture on the effects of biochar application, the still rather weak results in Siaya and the lack of effects in Embu might be explained by the high clay content of soil found at both sites. Since water is held stronger in smaller pores, clayey soil already shows high water retention (Krull et al., 2004), thus there might be less potential for further improvement through addition of biochar. Following charcoal addition Tyron (1948) even found a decrease in available moisture in clayey soil.

When comparing soil water retention of Siaya and Embu, it became clear that soil in Embu holds more water plant-available than soil in Siaya. Whereas Siaya holds water more strongly at the higher water tensions (pF of 3 and pF of 4.2) when compared to Embu. This indicates a higher clay content of soil in Siaya and probably a higher silt content of soil in Embu.

Actual data on soil texture and on further soil properties for both sites are essential to provide reliable explanations for the differences in results of Siaya and Embu. Therefore, the above made statements relating to clay content and soil texture are only assumptions.

The properties of the respective biochar type used in Siaya and Embu indicate that it would be more likely to find a positive trend and significant results for Embu than for Siaya. Table 3 reveals that coffee husk biochar features a higher surface area and organic matter content than maize cob biochar. Thus, application of coffee husk biochar could result in relatively greater improvement of soil moisture and water retention characteristics due to a higher addition of organic matter (see Chapter 2.3.1). The relatively higher surface area of coffee husk biochar when compared to maize cob biochar could go along with a higher amount of micropores. This indicates a higher chance of improvements in soil water retention and soil moisture with coffee husk biochar than with maize cob biochar. It should be noted that the porosity of biochar can increase with time, when biochar contains a high proportion of ash, since ash might leach from the pores (Lehmann & Joseph, 2009). As can be seen in Table 4 the ash content of coffee husk biochar is higher than the one of maize cob biochar. Although coffee husk biochar in general features a higher surface area and thus most likely higher microporosity, its pores may have been blocked by ash or the mineral fraction during the time soil samples were taken, as Herath et al. (2013) observed in their study. Moreover, biochar's potential hydrophobicity might also influence soil moisture and soil water retention (Mukherjee & Lal, 2014; Tyron, 1948). Since no actual data on properties of biochar used in Siaya and Embu is available so far, the above made statements relating to properties of biochar and its effects on soil moisture and soil water retention are only assumptions.

Sohi et al. (2009) argue that soil cover, soil temperature, evaporation and evapotranspiration influence available water in soil. Therefore, a comparison of water content between subplots may be disturbed by an effect of fertiliser and by indirect effects of biochar on plant growth and thermal properties of soil. Also Major (2009) argues that although biochar addition to a planted soil initially increases crop growth, water mobility later on decreases since an increased plant biomass and surface is exposed to evaporation, especially in clay soil. Influences through soil cover, soil temperature, evaporation and evapotranspiration are a possible explanation for the significant difference in soil moisture for subplots with added fertiliser and subplots without fertiliser. Subplots that received fertiliser treatment featured increased soil cover and thus probably lower soil temperature, decreased evaporation and increased transpiration when compared to subplots with no added fertiliser. In addition, soil samples taken in subplots with added fertiliser might contain more fine roots and thus feature higher soil moisture, although during soil sampling roots were removed manually as effective as possible.

5.4 Bulk Density

For Siaya, the lowest bulk density was found for the control treatment and the highest bulk density for the biochar rate of 1 t ha^{-1} and it was was significantly different from all other treatments. The means for the biochar rate of 0 t ha^{-1}, 5 t ha^{-1} and 10 t ha^{-1} are almost identical (Figure 10).

For Embu, the lowest bulk density was found for the biochar rate of 5 t ha^{-1}, and the highest bulk density was found for the biochar rate of 1 t ha^{-1}, these treatments were significantly different from each other (Figure 10).

Since the expectation of decreasing bulk density with increasing biochar rate was not fulfilled and the significant differences found are not conclusive, hypothesis 2 has to be falsified for both Siaya and Embu.

Although the bulk density of soil usually decreases through addition of biochar (see Chapter 2.3.2) the biochar rates applied might be too low to obtain differences for the clay soil found at both sites. Castellini et al. (2015) also found no significant effect of biochar addition on soil bulk density in a clay soil.

A Since biochar's properties in soil are influenced by field ageing, soil compaction and thus soil bulk density might only decrease in the long term, but not in the short term (Cheng & Lehmann, 2009; Mukherjee et al., 2011).

5.5 Macronutrient Content of Maize Leaves

For both Siaya and Embu no conclusive significant differences for increasing nutrient content (N, P, K, S) with biochar rate were found. Due to the small sample size and high variance the data has to interpreted with caution. Since not both, conclusive significant differences and a trend for increasing nutrient content with biochar rate has been found for any of the examined nutrients, hypothesis 3 has to be falsified for both Siaya and Embu.

In the following, the results for the respective nutrients are summed up shortly and afterwards possible reasons for the lack of effects of biochar are discussed simultaneously for all investigated nutrients.

For N content of maize leaves, no significant effect of the biochar rates but a significant effect of the presence of fertiliser was found in Siaya. For plots that received no fertiliser, significant differences for biochar rate were found, but did not follow a trend with increasing biochar rate, in Siaya. In Embu, no significant effect of the biochar rates and no effect of the presence of fertiliser on N content of maize leaves was found, although the mean score of presence of fertiliser is higher than the one for absence of fertiliser. The significant difference in N content for subplots with added fertiliser compared to subplots without added fertiliser can be explained by N contained in applied DAP fertiliser.

For P content of maize leaves, no significant effect of the biochar rates but a significant effect of the presence of fertiliser was found in Siaya and Embu. The significant difference in P content for subplots with added fertiliser compared to subplots without added fertiliser can be explained by P contained in applied DAP fertiliser. When data was split into two groups, one referring to plots amended with fertiliser and the other one not amended with fertiliser, a slight trend for increase of P content of maize leaves with biochar rate was found for plots not amended with fertiliser in Siaya and Embu.

For K content of maize leaves no significant effect of the biochar rates and no significant effect of the presence of fertiliser was found in both Siaya and Embu. The lack of significant differences between presence an absence of fertiliser can be explained by the fact that DAP fertiliser contains no K. Still the K content for soil samples with added fertiliser was higher than the K content of soil samples, which did not receive fertiliser. A slight trend for increase of K content of maize leaves for plots amended with fertiliser was found. In case N was a nutrient limiting factor prior application of fertiliser, availability of K might have increased following fertiliser application.

For S content of maize leaves no significant effect of the biochar rates and no significant effect of the presence of fertiliser was found in both Siaya and Embu. As for K content of maize leaves, the lack of significant differences between presence an absence of fertiliser can be explained by the fact that DAP fertiliser contains no S. When analysing data on sub-plots that received no fertiliser, for S significant differences dependent on biochar rate were found, but the significant differences found did not follow a trend with increasing biochar rate.

The following explanations refer to all investigated macronutrients contained in maize leaves (N, P. K, S),

In a lot of cases nutrient availability and nutrient use efficiency in soil, directly increases through the addition of nutrients contained in biochar and indirectly through improved nutrient retention, modified soil microbial dynamics and increased decomposition of organic material in soil (see Chapter 2.3.3).

There are various possible reasons for the lack of significant findings and positive trends in Siaya and Embu.

The biochar used both in Siaya and Embu is plant-derived and biochar based on plant materials often features a low concentration of nutrients and minerals, including N, P, K and S when compared to animal-derived biochar, like manure (Lehmann et al., 2003; Chan et al.,2008a; Waters et al., 2011; Major et al., 2010b). Therefore, a direct increase in nutrient availability through biochar addition might be too low for significant differences.

An indirect increase of nutrient retention and thus nutrient availability might be limited trough a lack of field ageing, since the incubation period of soil with biochar was still rather short until soil samples were taken. Field ageing has a favourable influence on all the following mentioned properties, including pH value, liming effect and CEC.

Biochar’s pH value increases over time due to surface oxidation (Cheng et al., 2008). Also liming effect is influenced by field ageing. Mukherjee et al. (2014) found an increase in ash content after ageing of biochar for 15 months. An increase in ash content goes hand in hand with an increase in pH value, which leads to increased nutrient availability and nutrient uptake by plants (Glaser et al., 2002; Lehmann & Rondon, 2006; Lehmann & Joseph, 2009). Biochar’s liming potential is dependent on the feedstock used. According to Kookana et al. (2011), biochar derived from plants features a lower neutralising capacity than biochar derived from animals, like manure.

Another considerable factor is CEC, which also increases gradually after incorporation in soil due to oxidiation (Verheijen et al., 2010). In addition, biochar based on plant feedstocks usually features a lower CEC than biochar based on plant-derived feedstocks (Scott et al., 2014).

To conclude, the actual nutrient content of biochar and the bioavailability of nutrients is highly dependent on the properties of feedstock used. Since no data on nutrient content of biochar used and soil found both in Siaya and Embu is available until now, the above made statements are only assumptions.

5.6 Moisture Content of Maize Leaves

For Siaya and Embu, there was no significant effect of the biochar rates and no significant effect of the presence of fertiliser on moisture content of maize leaves.

The lack of differences in moisture content of maize leaves at least indicates that the maize plants exhibit no nutrient deficiencies (Al-Abbas et al., 1972).

6 Conclusions and Outlook

Besides determining soil physical properties, like soil moisture, soil water retention and bulk density, this study also gave insight into soil fertility by looking into the nutrient and moisture content of maize leaves following biochar application. A broad range of biochar's impacts towards soil physical properties and soil fertility with focus on crop response was investigated, although only based on short-term effects.

In the context of this study, it would be interesting to review already existing results, including the ones in this thesis, in the light of actual data on soil at the investigated sites and biochar used. In addition, further soil and plant sampling in the following crop seasons is desirable, since effects on soil water characteristics and soil fertility might increase due to field ageing.

In a broader context, the development of an international database with properties of biochar, including pyrolysis system used and production conditions would be desirable in order to facilitate choosing the right biochar for respective applications, especially if instruments and facilities for testing biochar might not be available.

Overall, it became clear, that in order to allow for prediction of the effects of biochar in soil and in order to make large scale application possible, a deeper understanding of interactions between soil type, biochar production method, biochar feedstock, application rate and field crops is essential. More research in order to increase knowledge on all these interactions is especially important, since neutral or positive as well as negative impacts following biochar application are possible.

In the context of biochar as a possible tool towards increasing food security in tropical regions, like the investigated areas in Kenya, a deeper understanding of interactions and thus also further studies and experiments at field scale are necessary in order to rule out negative effects on plant growth, before broader application can take place.

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