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EFFECTS OF BIOCHAR ON SOIL PHYSICO- CHEMICAL PROPERTIES, GROWTH AND YIELD OF *BRASSICA NAPUS*

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ABSTRACT

The use of fragile marginal lands for crop production has led to the depletion of soil nutrients hence reduced agricultural productivity. Due to low productivity in the uplands, farmers have moved to cultivating fertile wetlands, where they mostly grow market gardening crops, such as vegetables for sale to nearby cities. Unfortunately, productivity is also decreasing in the wetlands due to nutrient mining where inadequate amounts of inorganic and organic fertilisers are applied since they are expensive and most farmers cannot afford. Organic fertilisers are an option, but because farmers have few livestock, the manure is not enough. For those that can apply organic manures, the benefits are short lived due to rapid decomposition of the manure. Under these scenarios, the use of biochar as an organic amendment can be a sustainable option. Biochar, a carbonaceous material, can be used to improve soil fertility and crop productivity. This study assessed the effects of four types of biochar pyrolysed from four sources: maize *(Zea mays)* stover, pine sawdust, soya bean (*Glycine max)* stover and thatch grass (*Hypharrenia filipendula)* stover on soil physico-chemical properties and the growth performance of rape (*Brassica napus*). The biochar was incorporated into the soil just before planting in a randomised complete block design (RCBD) and replicated three times. The *B. napus* was grown during the wet season and dry season of 2015 at Glen Avilin farm in Shamva. Four weeks after transplanting, the *B. napus* was harvested weekly for six weeks and assessed for fresh yield, moisture content, leaf length and leaf area over a two month growth period. Soil samples were collected at 0-10 cm, 10-20 cm and 20-30 cm depths before biochar application; after the first crop and after the second crop and were analysed for water holding capacity, pH, soil carbon (C), mineral N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). At each sampling point and soil depth, an undisturbed soil core was collected for bulk density determination. Data were analysed using Genstat version 14. Results showed significantly higher ($p<0.05$) fresh weight yield, leaf length and leaf area in plots amended with biochar than the control in both wet and dry seasons. In both the wet and the dry season, biochar application rate of 20 t/ha had the highest yield, leaf length and leaf area of *B. napus* across all the biochar types. Nutrient content was significantly high ($p<0.05$) in the 0-10 cm depth in the wet and dry season. Soil sampling depth had a significant effect on bulk density and water holding capacity. It was concluded that biochar may be a better option for improving soil nutrition status and productivity of *B. napus*. However, more studies are required to establish long term benefits of using biochar on soil fertility and crop yields.

Keywords: biochar, *Brassica napus*, feedstocks, soil properties, yiel

DECLARATION

I declare that the work contained in this thesis has not been submitted by me or any other person for any other award and that it is all my work. I also declare that all sources used or quoted have been indicated and acknowledged by means of complete references.

Name Lourene Rukondo

Signature

Date 20/11/2020

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DEDICATION

To my three boys, Blessing, Akudzwe and Akatendeka. I love you.

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LIST OF ACRONYMS

AAS	Atomic Absorption Spectrometry
ANOVA	Analysis of variance
BD	Bulk Density
RCBD	Randomised complete block design
DR&SS	Department of Research and Specialist Services
GHG	Greenhouse gases
MZ	Maize stover biochar
SOC	Soil organic carbon
SB	Soya bean stover biochar
SD	Sawdust biochar
SSA	Sub-Saharan Africa
TG	Thatch grass biochar
WHC	Water holding capacity

CHAPTER 1

1.0 INTRODUCTION

1.1 Background

The majority of Zimbabwean smallholder farmers live in marginal areas characterised by low rainfall and poor soil fertility. Continuous cultivation of available crop land has led to an increase in land degradation processes of soil nutrient mining and soil erosion (Yilanagai *et al.* 2014). The use of fragile marginal lands has culminated in reduced agricultural productivity. The marginal areas are more vulnerable to the negative impact of climate change because of inadequate rainfall and soils having low water retention capacity to sustain crop production. The loss of mineral nutrients from the soils under cultivation generally exceeds mineral nutrient inputs added by farmers and from mineralization process thus pose the greatest challenge to improving productivity without compromising sustainability. Maintaining soil fertility by overturning the nutrient imbalance encompasses returning nutrients removed by harvest and those lost via runoff, erosion and other pathways back to the soil. Therefore, to compensate for the depletion in soil nutrient status and retain soil fertility, farmers need to apply soil amendments on a regular basis. However, inorganic fertilisers are expensive and beyond reach for most smallholder farmers. The best alternative option would be the use of organic nutrient sources such as livestock manure. However, livestock manure quickly decomposes and the quantities are not enough to meet the need of all smallholder farmers as some do not even own livestock. Organic amendments such as biochar are sustainable long term options. Biochar lasts longer in the soil and is pyrolysed from locally available raw materials such as veld grass, crop residues and manure (Nigussie *et al*. 2012). Biochar amendment also leads to increased carbon concentration in the soil (Yanai *et al*. 2007).

More than 80% of the terrestrial organic carbon stocks are contained in the soil (IPCC 2000). However, efforts aimed at achieving carbon sequestration in the soil are offset by rapid decomposition and loss of carbon through greenhouse gas emissions (Lehmann *et al.* 2006). Moreover, tropical soils generally show low potential to accumulate carbon, due to high decomposition rates (Post and Kwon 2000). The consensus being that soil provides a window of opportunity for reducing carbon emissions. However, this can be easily depleted by land use change and uses such as cultivation (Lal 2004). Under these circumstances, the use of biochar may be a long term sustainable option for increasing soil carbon stocks.

Biochar is a stable solid, rich in carbon and can last in the soil for a long period of time and has a potential to mitigate climate change (Verheijen *et al.* 2009). It is produced by pyrolysis of biomass under high temperatures and anaerobic conditions. The products of pyrolysis also include syngas and bio oil. Yield of biomass pyrolysis differ with temperatures and type of feedstock (Sohi *et al*. 2009). Temperatures between 400^{o}C and 500^{o}C produce more char while temperatures above 700^{o}C favour the production of bio-oil and syngas (Sohi *et al*. 2009). Crop residues, veld grass, sawdust, chip wood, animal manure and many other organic wastes can all be used in the production of biochar. Biochar can also improves soil physical properties and it can be used as a soil amendment for improved plant growth. Although biochar research in Sub-Saharan Africa is still limited, studies conducted elsewhere demonstrated the capacity of biochar to enhance soil structure, nutrient availability, moisture retention, sorption of pollutants, and crop emergence and productivity (Lehmann *et al.* 2008; Verheijen *et al.* 2009; Free *et al.* 2010; Laird *et al.* 2010; Van Zwieten *et al*. 2010).

The physical and chemical properties of the biochar depend on the types feedstocks used to produce the biochar, as well as the pyrolysis temperature (Enders *et al*. 2012, Spokas *et al*.

2012). Biochars from plant material have high C content and low amounts of nutrients than manure based biochars. (Cantrell *et al*. 2012). Some studies also show that plant material biochars have lower C, higher pH and higher N than those biochars from woody biomass (Novak *et al.* 2009, Amonette and Joseph 2009). In addition, biochars produced by fast pyrolysis have large surface area, high adsorption rate and high carbon content (Enders *et al.* 2012). Total P content is high in fast pyrolysis biochars, contrasted to total N that decreases with increasing pyrolysis temperature (Zheng *et al*. 2013). Approximately half of the N is lost during pyrolysis due to volatilisation and conversion of nitrogen containing structures (amino sugars, amines and amino acids) into recalcitrant forms, and the N retained in the biochar is not bio available (Cao and Harris 2010). Biochar retains most of the mineral content of the feedstocks (Amonette and Joseph 2009).

Smallholder farmers in Zimbabwe cultivate fragile wetlands where they establish gardens as a climate change adaptation strategy. Continuous cultivation of these gardens may result in soil degradation with over exploitation and loss of soil organic carbon (SOC), soil structure, water holding capacity and porosity, leading to a reduction in agricultural productivity. The use of biochar can therefore reduce the rate of soil degradation by improving soil aggregation, fertility and productivity. Biochar also reduces the need for inorganic fertilisers thereby reducing costs and emissions from fertiliser application. Therefore, this study evaluated the effects of different forms of biochar on soil physico-chemical properties and plant growth in a wetland garden cropped to *B. napus.*

1.2 General Objective

To investigate the effects of biochar on soil physical and chemical properties and growth of *B. napus* grown in wetland gardens.

1.2.1 Specific Objectives

1. To assess the effects of biochar pyrolysed from different feedstocks (veld grass, saw dust, soya bean stover and maize stover) on soil physical chemical properties and growth performance of *B. napus*.

2. To determine the effects of different application rates of biochar pyrolysed from different feedstocks (veld grass, soya bean stover and maize stover) on soil physical, chemical properties and on growth performance of *B. napus.*

1.2.2 Hypotheses

1. H_0 The type of biochar feedstock has no effect on soil physical, chemical properties and growth performance of *B. napus*

2. H_0 The application rates of different types of biochar feedstock have no effect on soil physical, chemical properties and growth performance of *B. napus.*

1.3 Outline of the thesis

In order to satisfy the objectives and the hypotheses outlined in section 1.2, the thesis has been structured into seven chapters:

Chapter 2 gives an account on the literature on the effects of biochar from various feedstocks at different application rates on plant growth and soil physical and chemical properties.

Chapter 3 describes the materials and methods used to achieve the stated objectives

Chapter 4 assessed the effects of four different types of biochar on soil physical, chemical properties and the growth performance of *B. napus.* Biochar was produced from maize stover, sawdust, *Hyparrhenia filipendula* and soya bean stover.

Chapter 5 investigated the effects of different biochars application rates on the growth performance of *B. napus,* soil physical and chemical properties.

Chapter 6 gives the main conclusions from the entire work and recommendations on improving agricultural production in Zimbabwe.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Biochar production and its uses

Biochar is carbon rich material that is produced when biomass is heated in an oxygen limited environment, a process known as pyrolysis (Lehmann and Joseph 2009). During the pyrolysis of biomass, biochar, syngas and bio-oil are produced and can be used as sources of renewable energy (Ameloot *et al.* 2012). Biochar differs from charcoal in that biochar is used as a soil amendment as well as for carbon sequestration (Fig 2.1). Traditional charcoal, produced after the burning of wood is an example of biochar (Woolf 2008). Biochar is applied to agricultural soils to improve soil fertility for crop production as well as carbon sequestration and climate change mitigation (Ernsting 2011).

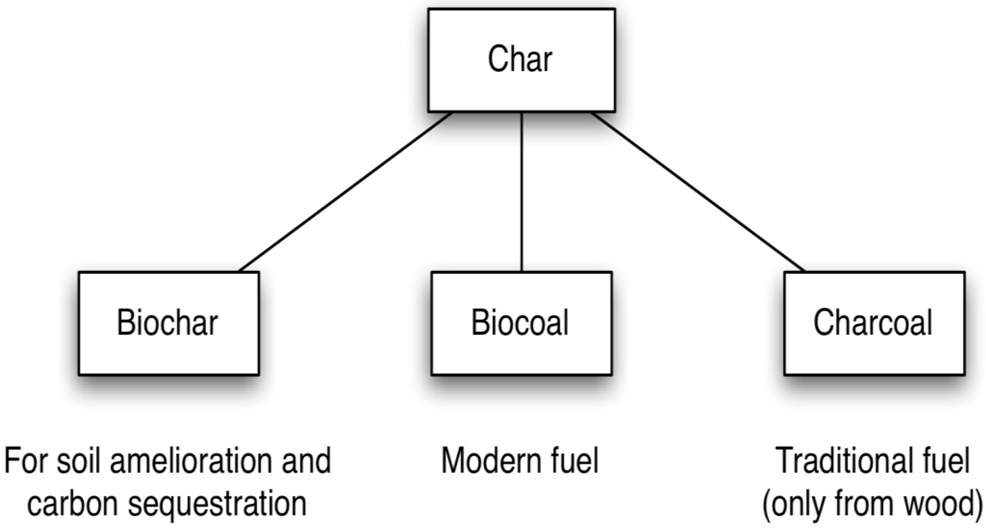

Fig 2.1. Nomenclature for chars (Schouten 2010)

Biochar can be produced from different feedstocks including manure, wood, crop residues etc. Each biochar feedstock produces biochar with different properties. Different pyrolytic temperatures lead to different proportions of biochar, syngas and biochar (Table 2.1) and therefore one can tailor their pyrolysis conditions to suite their desired outcome

(Krishnakumar *et al.* 2013). Fig 2.2 shows the pyrolysis process of biomass to produce biochar.

Table 2.1. The mean post-pyrolysis feedstock residues resulting from different temperatures and residence times.

Mode	Conditions	Liquid (%)	Biochar (%)	Syngas (%)
Fast pyrolysis	Moderate temperature, ~500°C, short hot vapour residence time of ~ 1 s	75	12	13
Intermediate pyrolysis	Moderate temperature ~500°C, moderate hot vapour residence time of 10 – 20 s	50	20	30
Slow pyrolysis (Carbonisation)	Low temperature ~400°C, very long solids residence time	30	35	35
Gasification	High temperature ~800°C, long vapour residence time	5	10	85

Source: Krishnakumar *et al.* (2013).

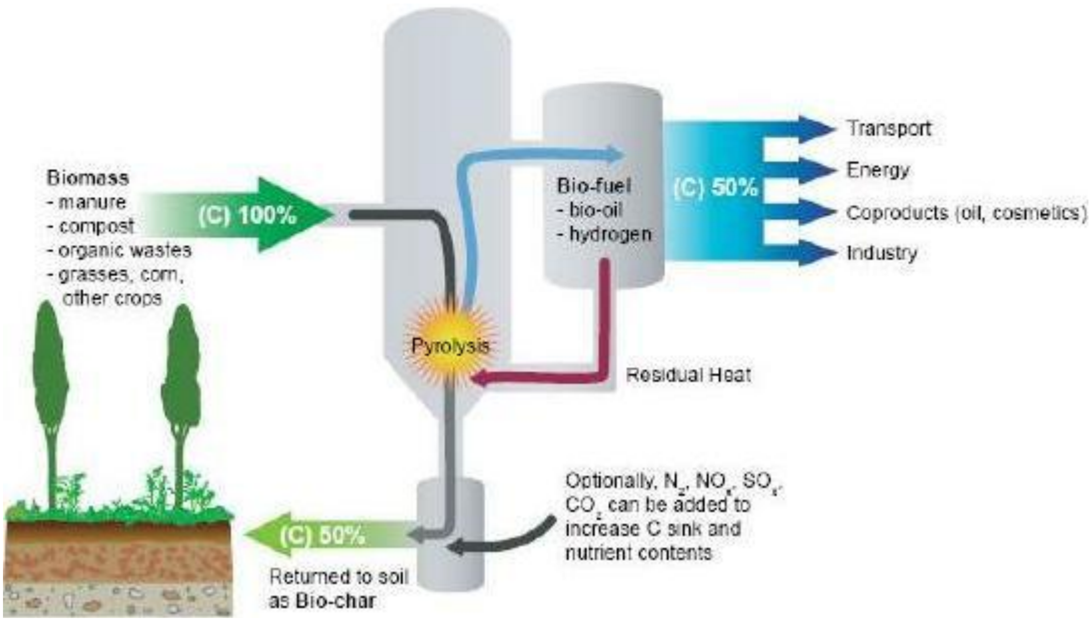

Fig 2.2 Biochar production and generation of bio-energy (Lehmann 2007)

The syngas produced during pyrolysis is flammable (contains methane and other hydrocarbons). The gases may be liquefied and used as a source of fuel (Krishnakumar *et al.* 2013).

Biochar may also contain some toxic matter for example lead, copper and arsenic but these toxic elements may cause less harm as compared to the feedstock since biochar is recalcitrant (Farell *et al*. 2013). The biochar is hard to mineralise and therefore the release of the toxic elements in the macromolecular structure is reduced (Chen and Yuan 2011, Santos *et al.* 2012). A survey by Scholz *et al*. (2014) showed that there were several technologies that can be used to produce biochar and the choice of the technology for biochar production is mainly influenced by the type of feedstocks, access to technology and resource availability.

2.2 Potential of biochar utilisation in Sub-Saharan Africa

Crop production in the Sub-Saharan Africa (SSA) is under threat due to soil degradation (Diagna 2003) leaving farmers with no other option but to use inorganic fertilisers. However, inorganic fertilisers may result in addition of more nitrogen at the expense of other major and micronutrients (Lal 2009). The nutrients supplied by inorganic fertilisers are often quickly lost through volatilisation and or leaching (Savci 2012). Moreover, most smallholder farmers either lack resources to purchase the inorganic fertilisers (Markwei *et al.* 2008) or have inadequate knowledge on their sustainable use resulting in pollution of surface water resources as well as increased greenhouse gas emissions (Savci 2012).

The SSA region is the most affected region by climate change which has a direct impact on agricultural productivity (Mekuria and Noble 2013). Like other developing economies, smallholder farmers depend on agriculture for subsistence and for cash income. Therefore, if practised in unsustainable way, subsistence agricultural practises can result in the transfer of carbon from the soil to the atmosphere as CO_2 and CH_4. Agricultural activities contribute 10-12% of greenhouse gas emissions worldwide (Jaiaree *et al.* 2006; Smith *et al*. 2008) and atmospheric CO_2 concentrations can be reduced by improved land management practices (FAO 2010). Therefore, smallholder farmers in SSA may use biochar as a sustainable option because it can be produced using locally available materials and can increase carbon sequestration in the soil (Kiers *et al.* 2008). The use of biochar by smallholder farmers in SSA have the potential to increase productivity and therefore contribute to improving food security (Yilangai *et al*. 2014).

Biochar amendments may improve nutrient cycling, boost soil organic carbon pools and improve crop productivity (Laird *et al.* 2009). On the other hand, the application of biochar in nitrogen deficient soils may reduce crop productivity due to immobilisation of N (Lehmann *et al.* 2006). Therefore farmers may risk a reduction in the crop production since biochar effects are inconsistent (Mekuria and Noble 2013). Moreover, for smallholder farmers in the SSA, materials for biochar production can also be a source of energy and alternative source of animal feed hence there are competing uses which can affect its uptake.

2.3 Relationship between biochar and soil productivity

Maintaining long term soil fertility is essential to attain optimal productivity from the soils. Soil organic amendments such as manure and compost have been successfully applied to the soil, supplying it with nutrients for crop uptake, enhancing the nutrient cycles (Goyal 1999) and improving soil moisture content. However, the benefits are short lived due to high decomposition rates requiring annual application of amendments to sustain crop productivity. In this regard, the use of biochar becomes a possible long term solution for stabilising carbon storage in the soil as it can last for a long time. Biochar is a carbon-rich by product from biomass pyrolysis. The characteristics of biochar vary widely depending on the feedstock, pyrolysis temperature and pyrolysis duration (Verheijein *et al*. 2010). Primary use of biomass at high temperature is for energy production because at high temperature, more energy and less biochar is produced. Moreover, biochars produced at high temperature have a higher surface area and a greater mineral and ash content than biochar produced at low temperature (Krishnakumar *et al*. 2013).

Much of the interest in using biochar as a soil amendment comes from studies based on Amazonian soils where the presence of charcoal was associated with significant improvements in soil quality and crop yields (Lehmann and Joseph 2009). Biochar can increase the productivity of the soil (Lehmann *et al.* 2003). Immediate positive effects of biochar addition for nutrient availability are mainly due to an increase in the macro and micro nutrients. The macro-nutrients enriched in the soil from biochar addition are mainly K, Ca and P and the micro-nutrients include Zn and Cu (Lehmann *et al*. 2003). The long term benefits for biochar addition include nutrient retention, stabilisation of organic matter and slower nutrient release from added organic matter. Biochar does not directly provide nutrients but it improves the soil structure and water retention capacity, lowers acidity and reduces aluminium toxicity to plant roots. Biochar also lowers the availability of heavy metals, therefore, has a potential in bioremediation (Winsely 2007). Biochar can increase crop productivity depending on soil type, crop type, biochar concentrations, nutrient levels and biochar surface area (Winsely 2007; Laird *et al.* 2010). Biochar tends to recycle nutrients that are removed when biomass is harvested. Most biochars act as a liming agent since base cations (for example calcium, potassium and magnesium) in feedstock are transformed into oxides, hydroxides and carbonates during pyrolysis. Biochar also reduces soil bulk density and hence increases water infiltration, root penetration and soil aeration (Lehmann and Joseph 2009).

2.4 Relationship between biochar application rates and crop productivity

Application rates of biochar vary according to the type of feedstock used, the levels of metal contamination in the feedstock, the amounts of nutrients in the feedstocks as well as the climatic conditions of the area where the biochar is to be applied (Krishnakumar *et al.* 2013). Application rates that range from 5t/ha to 50 t/ha on different crops have been used successfully in other studies (Krishnakumar *et al.* 2013; Major 2013). However, optimal application rates of biochar need to suit local conditions. Dugan *et al.* (2010) stated that water holding capacity was increased when biochar was applied at different rates compared to zero application. Winsely (2007) reported that significant productivity gains are possible at biochar application rates of 0.4 t/ha to 8 t/ha. Biochar amended together with inorganic fertilisers was found to improve crop yields (Yamato *et al.* 2006; Chan *et al.* 2007; Purakayastha 2010). According to Chan *et al.* (2007), animal manure biochars improved crop productivity when applied at 10t/ha. Moreover, studies indicate that legumes thrive in high biochar concentrations, probably due to the fact that their nitrogen fixing ability enables them to compensate for limited nitrogen availability in the soil Krishnakumar *et al*. (2013). Biochar amendment increases plant growth, yield as well as seed germination (Graber *et al*. 2010). Zheng *et al*. (2013) reported that while increasing the application rate of biochar did not increase the rate of biomass production, its application alone improved plant growth. The improved plant growth was attributed to improved soil physical properties which enhance root growth in the amended plots as compared to the unamended control (Zheng *et al.* 2010). Other studies also show that crop productivity increase significantly with increased biochar application rates either when used alone (Yeboah *et al.* 2009), or in combination with inorganic fertilisers (Arif *et al*. 2012).

2.5 Biomass used to produce biochar

Biochar can be produced from any plant and crop biomass as well as organic wastes, for example, urban green waste, agricultural wastes, bagasse, animal manures and paper products (Lehmann and Joseph 2009). The biomass used to produce biochar determines the properties of the biochar produced (Scholz *et al*. 2014). For example, Raveendran *et al*. (1995) found biochar produced from rice husk having higher ash content than biochar derived from maize cobs. Biochar produced from nutrient rich feedstocks (for example animal manure) has more nutrient benefits (Chan *et al.* 2007) than nutrient poor feedstocks. Biochar produced from wood biomass have larger surface area than biochar produced from grasses (Mukherjee *et al.* 2011; Kloss *et al.* 2012). Lehmann and Joseph (2009) outlined a number of factors to be taken into consideration when choosing a feedstock for biochar production and these included the moisture content of the feedstock and the distance of the pyrolysis site from the biomass source. This will reduce on the cost of biochar production. Furthermore, concentrating on the "true waste" as feedstocks for biochar production would also maintain a low cost production system (Whitman *et al.* 2010; Dicknson *et al.* 2015). True wastes refer to biomass which when used as a feedstock will not disturb any local carbon and nutrient cycling as compared to when crops or forests are cleared for biochar production.

The effects of biochar are mostly positive. However, Rogovska *et al.* (2012) found that some biochars may have adverse, negative effects and some may have the ability to absorb and neutralise phytotoxic compounds found in the soil. Streubel *et al.* (2011) reported that biochars, regardless of their origin, significantly raised the pH of all soil types with the greatest impact on sandy soils because of their poor buffering capacity.

Moreover, different biochar feedstocks also have different effects on the quality of biochar. Therefore, application of biochar from different feedstocks results in different impacts on crop yields, soil nutrient dynamics and biochar stabilities. Total carbon content of biochar varies depending on the feedstocks used (Gaskin *et al.* 2010). The highest carbon content is obtained from hard wood biomass pyrolysed at high temperature, while manures generate biochar with low carbon content. Relative to woody biomass, nutrient-rich manures contain more minerals which end up in the biochar, and thus reduces the carbon proportion. For example biochars produced from pine chips had a carbon content of 817 g/kg when produced by slow pyrolysis at 500^{o}C, while poultry litter ended up with 399 g/kg (Gaskin *et al.* 2010).

The quality of feedstocks and pyrolysis temperature play an important role in the chemical and physical properties of the biochar (Joseph *et al.* 2010). Woody feedstocks produce more biochar that has a high C content of up to 80% and C:N ratios ranging between 200 to 600 compared to herbaceous feedstocks with a lower C:N ratio. Herbaceous and straw based feedstocks have lower C content (66%), higher soluble elemental composition and higher pH compared to woody based biochars (Novak *et al.*2009). Cations present in the biomass are modified during pyrolysis into hydroxides, oxides and carbonates and these result in biochar working as a liming agent in the soil (Glaser *et al.* 2002). Increasing the pyrolysis temperature leads to the production of biochar with a high surface area which improves water holding capacity in sandy soils (Kloss *et al*. 2012).

2.6 Effects of biochar on soil properties

The pH of biochar varies with the type of feedstock. Some studies revealed an increase in the soil pH when biochar was used as an amendment in acidic soils (Chan *et al.* 2008; Laird *et al.* 2010; Van Zwieten *et al.* 2010; Peng *et al.* 2011; Jones *et al.* 2012; Xu *et al.* 2013). When soil pH is low for a particular use, an increase in pH can provide a variety of benefits especially by chemically enhancing the availability of plant nutrients. However, the pH of biochar is usually above 9 and can serve as a liming agent. Biochar amendment results in improved soil pH and hence improved nutrient availability (Glaser *et al.* 2002; Lehmann and Rondon 2006). Glaser *et al*. (2002) also found that pH values of soils increased more after addition of hardwood biochar (pH 6.15) than conifer biochar (pH 5.15) mainly due to their different ash contents of 6.38% and 1.48% respectively. In this regard, hardwood biochars have a larger influence on soil fertility (Steiner 2007) than other types of biochars. Additionally, increased pH of the soil stimulates microbial activity thereby promoting mineralisation of soil organic matter. Moreover, an increase in the pH results in a decrease in aluminium saturation and an increase in cation exchange capacity and base saturation.

The type of feedstocks and pyrolysis temperature mainly determine the carbonate concentrations of the biochar, making some biochars better liming agents than others. Van Zwieten *et al*. (2007) found the carbonate content in biochar facilitating liming in soils and raising the pH of acidic or neutral soils. Zheng *et al*. (2010) found that biochar application led to increased cation exchange capacity (CEC) as well as available phosphorus content of the soil, but reduced the nitrate-N available in the soil. According to Soderberg (2013), soil analytical results showed that biochar amendments significantly increased soil pH, carbon content as well as Ca and Mg content.

An increase in the pH of acidic soils also leads to an increase in nutrient availability (K, Ca, Na, Mg and P) (Atkinson *et al.* 2010; DeLuca *et al.* 2006 Xu *et al.* 2013) and increases the solubility of ammonium (NH_4^+) but N decreases due to adsorption thereby reducing the soil nitrogen (Xu *et al.* 2013). Biochar amendment affects the soil physical properties that include soil structure, pore size, bulk density, soil aeration and water holding capacity. Downie *et al.* (2009) reported that addition of biochar to the soil leads to an improvement in soil water retention capacity and soil aeration, especially in clayey soils due to improved porosity.

Biochar has a low bulk density of 0.3 Mg/m^3 (Downie *et al.* 2009) which is lower than that of mineral soils (1.3 Mg/m^3 for soil). Hence, biochar amendment will reduce the overall soil bulk density (Oguntunde *et al.* 2008; Jones *et al.* 2010; Laird *et al.* 2010; Chen *et al.* 2011; Mankasingh *et al.* 2011; Basso *et al.* 2012; Zhang *et al.* 2012) (Table 2.2) resulting in increased soil water holding capacity desirable for plant growth (Brady and Weil 2004). The lowered bulk density of soils can be taken as an indicator of improved soil aggregation and soil aeration (Krishnakumar *et al.* 2013). This is supported by Basso *et al.* (2012) who showed that a decrease in soil bulk density led to an increase in soil aeration and porosity thereby enhancing root growth. However, Rogovska *et al.* (2011) stated that although soil bulk density may be reduced prior to application of biochar, it may increase over time as a result of compaction.

Table 2.2 Impact of biochar application on soil bulk density.

Soil type	Biochar type	Study type	Biochar application rate % (gg^{-1})	Bulk Density g/cm^3	Reference
Norfolk loamy sand: E	Pecan (*Carya illinoinensis*) shells, 700^{0}C	Laboratory	(i) 0 (ii)2.1	1.52 1.45[1]; 1.52[2]	Busscher *et al.* (2011)
Hydroagric stagnic anthrosol	Wheat (*Triticum* spp) straw, 350-550^{0}C	Field	(i) 0 (ii) 1.1 (iii) 2.2 (iv) 4.4	0.99, 0.94[3] 0.96, 0.91[3] 0.91, 0.86[3] 0.89, 0.88[3]	Mankasingh *et al.* (2011)
Residue sand	Municipal green waste, 450^{0}C	Laboratory	(i) 0 (ii) 2.6 (iii) 5.2	1.65 1.55 1.44	Jones *et al.* (2010)

[1]measured after 44 days; [2]measured after 94 days; [3]measured after one year.

Source: (Mukherjee and Lal 2013)

The greater surface area and porosity of biochar improves aggregation and soil structure and improved soil water retention (Atkinson *et al.* 2010; Laird *et al*. 2010; Verheijen *et al.* 2010;

Uzoma *et al.* 2011). Water retention increases with improvements in soil aggregation and structure after biochar amendment (Brodowski *et al.* 2006) but the extent depends on the soil type. Addition of biochar to sandy soils resulted in an 18% increase in plant available moisture after adding 45% biochar by volume (Laird *et al.* 2010; Krishnakumar *et al*. 2013), whilst there were no changes in loamy soils and a decreased plant available moisture in clayey soils (Tyron 1948) due to the hydrophobic status of biochar (Glaser *et al*. 2002). Water use efficiency after biochar application was increased from 50% to 100% after increased application rates from 15 to 20 Mg/ha (Megagrams per hectare) (Uzoma *et al.* 2011). Amendment of biochar made from hardwood also resulted in an increase in water retention (Laird *et al.* 2010). This increase in soil moisture retention increases crop yields (Basso *et al.* 2010).

2.7 Biochar and greenhouse gas emissions

Carbon dioxide (CO_2) is a significant greenhouse gas (GHG) (Verheijen *et al*. 2010) in addition to nitrous oxide (N_2O) and methane (CH_4). Wood has a carbon content of 50% whilst biochar has a carbon content of 70-80% (Winsley 2007) and the carbon in biochar can be permanently sequestered in the soil. However, the effectiveness of biochar to reduce soil CO_2 emissions depends on the soil environment, the microbial community present and the physical and chemical properties of the biochar. N_2O and CH_4 gases are more potent than CO_2 by about 298 and 21 times respectively (Forster *et al.* 2007) and their emission levels vary with biochar type and soil conditions.

The production of biochar from plant biomass, and its subsequent application to agricultural soils such as communal gardens has the potential to minimize environmental risks while enhancing soil quality. The application of biochar may be a sustainable option for maintaining and sequestering SOC. Therefore, this study evaluated the effects of different biochars applied at varying rates on soil physico-chemical properties and growth of *B. napus*.

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Study area

The study was carried out at the Glen Avilin Farm, situated approximately 12 kilometers East of Bindura town, Mashonaland Central in Zimbabwe (21^{o} $04^{'}$ $40^{''}$S ; 30^{o} $46^{'}$ $45^{''}$E). The farm lies in natural region IIa of Zimbabwe, with a mean annual rainfall of 800 mm. The mean minimum temperature is 13^{0}C and the mean maximum temperature is 23^{0}C (Mugandani *et al*., 2012). The soils are classified as fersiallitic clays (5E) according to the Zimbabwe soil classification system (Nyamapfene, 1991).

3.2 Production of biochar

Biochar was produced from the pyrolysis of the following feedstocks: maize (*Zea mays* L) stover, thatch grass (*Hyparrhenia filipendula*), soya bean (*Glycine max*) stover and pine saw dust. The raw organic materials (feedstocks) were collected locally in Bindura. The feedstocks were sun dried to approximately 20% moisture content. Biochar was produced using batch reactors. Feedstocks were fed in a 210 litre metal reactor closed with a metal lid. The lid and the bottom of the reactor were fitted with 'Z' shaped handles to facilitate turning, mounted on a furnace made of bricks and raised to 40 cm above the ground. Coal was the source of energy for pyrolysis and 7.5 kilograms of coal were used for each batch. Temperature in the reactor ranged 300 to 500°C (Gwenzi *et al.* 2015). The reactor was turned after every 30 minutes to allow all the feedstock material to be charred. After 4 hours, the reactor was removed from the furnace and biochar was allowed to cool before packaging into polythene bags. The process was repeated for all the four feedstocks after which the biochar was taken to the field for application. Initial nutrient content of biochar was analysed from samples collected after pyrolysis.

3.3 Experimental procedure

Experiment 1: Effects of biochar amendment on selected soil chemical properties, bulk density, water holding capacity and plant growth.

The four biochar types were applied at a rate of 10 t/ha) (Nigussie *et al*. 2012) and a control which was unamended. The experimental plots measured 2 m x 1 m. The plots were arranged in completely randomised block design (CRBD) with slope as a blocking factor. The treatments were replicated three times at distances of 1 m between the plots and 2 m between the blocks. The biochar was weighed, spread in each plot and was immediately incorporated into the soil up to 30 cm using a hoe. The layout of the plots is illustrated in Figure 3.1.

Block 1

PLOT 1 Maize stover biochar	**PLOT 2** Control	**PLOT 3** Thatch grass biochar	**PLOT 4** Sawdust biochar	**PLOT 5** Soya bean residue biochar

Block 2 **2 m**

PLOT 1 Sawdust biochar	**PLOT 2** soya bean residue biochar	**PLOT 3** Maize stover biochar	**PLOT 4** Thatch grass biochar	**PLOT 5** Control

Block 3 **2 m**

PLOT 1 Thatch grass biochar	**PLOT 2** Soya bean residue biochar	**PLOT 3** Sawdust biochar	**PLOT 4** Control	**PLOT 5** Maize stover biochar

Fig 3.1 Layout of experimental plots for Experiment 1 with plots measuring 2 m x1 m.

Experiment 2: The effect of type and application rate of biochar on selected soil chemical and physical properties and plant growth.

The same sources of biochar used in Experiment 1 were used in this experiment. However, the biochar was applied at different application rates. The experimental plots measured 2 m x 1 m. The experiment was set up as a 3 x 4 factorial in a randomised complete block design (RCBD) was used and replicated three times. The first factor was biochar type with three treatments which are maize stover biochar, thatch grass biochar and soya bean stover biochar. The second factor was rate of application of biochar treatments with four treatments which are 5, 10, 15 and 20 t/ha). The biochar was weighed, spread in each plot and quantity depended on application rate and was immediately incorporated into the soil up to 30 cm using a hoe.

The layout of the experimental plots is shown in fig 3.2.

BLOCK1

TG5	SB15	MS5	TG15	SB5	MS20	MS10
	TG20	SB20	MS15	TG10	SB10	

2 m

BLOCK 2

TG10	MS5	SB5	MS10		MS15	SB10
SB15	TG5	TG20	SB20	TG15	MS20	

2 m

BLOCK 3

SB10	TG20	MS5	SB15	TG5	SB20	MS10
MS20	SB5		TG15	MS15	TG10	

Fig 3.2. Layout of experimental plots for Experiment 2 with plots measuring 2 m x 1 m.

KEY:

TG= Thatch grass biochar; MS=Maize stover biochar; SB= Soya bean biochar. Numbers represent the rate of application in t/ha.

3.4 Assessment of plant growth

Brassica napus seedlings (variety, Hobson giant) were sourced from Farmash Organic Nursery in Greencroft, Harare. The seedlings were planted at a spacing of 20 cm in-row and 30 cm inter-row in all plots. The first planting was done during the wet season (26 February-27 May 2015) and the second planting was done during the dry season (31 August-25 November 2015). Each plot had a population of 27 plants. The plots were watered regularly to keep the soil moist and weeds were handpicked when necessary. From the fifth week onwards, the plots were cultivated once a week using a hoe. A net plot of 1 m x 1 m was harvested from four weeks after planting at a weekly interval for five weeks and thereafter twice fortnightly. The fresh weight yield was recorded after which the *B. napus* leaves were oven dried at 105°C for 48 hours and the dry weight was recorded. Leaf length was measured using a 30 cm ruler and leaf area was estimated using the graph paper method. The growth of *B. napus* was quantified by measuring the yield, leaf length and leaf area. Moisture content was also determined from the fresh weight yield and the dry weight. For the dry weight, the *B. napus* leaves were first air dried and then oven dried at 60°C for 48 hours and weighed. The moisture content of the B. napus leaves was then calculated using formular I:

$$\text{Moisture content} = \frac{(\text{Wet weight} - \text{Dry weight})}{\text{Wet weight}} \times 100 \qquad \text{(Equation I)}$$

3.5 Soil analyses

Soil samples were collected before application of biochar, after one week the first crop (wet season) and finally one week after the second crop (dry season) in all the plots. Three sub-samples were collected from each plot and were thoroughly mixed to obtain a composite sample from the depths of 0-10 cm; 10-20 cm and 20-30 cm using a soil auger. The soil samples were put in zipper bags and labelled, then air dried at the laboratory and analysed for N, P, K, Ca, Mg, soil organic carbon (SOC), pH and water holding capacity at Bindura University laboratory, Astra Campus.

In addition, core samples were collected from each plot at 0-10 cm, 10-20 cm and 20-30 cm depths and sealed in a zipper bag to minimise loss of moisture and were used to determine soil bulk density.

Soil organic C was determined by the Walkley-Black method (Walkley and Black 1934) (appendix 1) where the oxidation of C was done using potassium dichromate and digestion using sulphuric acid. After digestion titration of excess dichromate was done using ferrous ammonium sulphate and ferroin indicator. The amount of organic carbon was then calculated as follows (Walkley and Black 1934):

$$\%OC = \frac{(B-S)*M \text{ of } Fe*12*100}{g*4000} \quad \text{(Equation II)}$$

Where B: Volume of ferrous sulphate solution used to titrate blank (ml)

S: Volume of ferrous sulphate solution used to titrate sample (ml)

M: Molarity of Fe

12/4000: milliequivalent weight of C (g)

g: weight of soil

To determine P, K, Ca, Mg and Na, the Mehlich 3 method was used (Ziadi and Sen Tran 2006) (appendix 2). Briefly, a soil sample of 3 g was weighed and mixed with 30 ml of extracting solution then placed on a reciprocating shaker at 120 oscillations per minute for 5 minutes. The solution was filtered into plastic vials. P was determined using the manual colorimetric method at 845 nm. Ca and Mg were determined by atomic absorption and K and Na using flame emission. The soil samples were sent to the Department of Research and specialist services (DR&SS) for N analyses using the Kjeldahl method. The pH was measured using the calcium chloride method (appendix 3). 15 g of soil were weighed in a beaker and 75 ml of 0.01M calcium chloride solution was added to the soil and shaken on a reciprocate shaker for 30 minutes. Soil pH was then measured using a pH meter (ADWA; AD1020) at room temperature. The electrodes were washed with distilled water after each reading.

Bulk density was determined using 100 cm^3 cores. The samples were oven dried at 105°C for 24 hours and then weighed. Bulk density was then calculated as follows:

$$Bulk\ density = \frac{\text{mass of oven dry soil}}{\text{volume of the core}}\ (g/cm^3) \qquad \text{(Equation III)}$$

A procedure by Dugan *et al.* (2010) was used to determine water holding capacity (WHC). Air dried soil was soaked in water for approximately 6 hours and then drained overnight. The drained soil was put in a pre weighed beaker (M_1). The weight of the moist soil and beaker (M_2) was recorded. The moist soil samples were put in an oven at 105°C for 48 hours for drying. The weight of the dry soil together with the beaker (M_3) was recorded. WHC of the soil was determined as follows:

$$WHC(\%) = \frac{M1-M2}{M3-M1} \times 100 \qquad \text{(Equation IV)}$$

CHAPTER 4

4.0 The influence of biochar pyrolysed from different feedstocks on soil physical, chemical properties and growth performance of *Brassica napus* (rape)

ABSTRACT

Continuous use of land without organic amendments causes degradation and decline in agricultural productivity associated with nutrient mining and crop harvesting. The use of biochar can be a sustainable option due to its long residence time in the soil and slow release of nutrients. This study assessed the influence of biochar from maize *(Zea mays)* stover (MZ), pine (*Pinus patula*) sawdust (SD), soya bean (*Glycine max)* stover (SB) and thatch grass (*Hypharenia filipendula)* (TG) on soil physical, chemical properties and growth of *Brassica napus.* Biochar was made using the batch process with coal as a source of fuel. Pyrolysis temperature ranged between 350-500°C. The biochars were incorporated into experimental plots before planting in a randomised complete block design (RCBD) and replicated thrice. The *B. napus* (Hobson giant) was grown during the wet season and dry season in 2015 at Glen Avilin farm in Shamva, Zimbabwe. The *B. napus* was harvested weekly after four weeks for three weeks and thereafter fortnightly. The leaves were assessed for fresh yield, moisture content, leaf length and leaf area. Data was analysed using Genstat version 14. The results showed significant differences ($p<0.05$) in fresh weight yields after biochar amendment in the wet and dry season. However, no significant differences were found among biochar treatments. Leaf length and leaf area were also significantly greater ($p<0.05$) in biochar treatments than the control with soya bean stover biochar treatments having the highest leaf length and leaf area. Moisture content of *B. napus* in plots amended with MZ biochar had significantly higher moisture content than the other treatments in the dry season. Biochar application resulted to a significant effect on soil chemical properties in different soil depths in the wet and dry season. Soil pH was significantly high ($p<0.05$) in the 0-10 cm depth in the dry season after biochar amendment. The concentration of the C, Ca, Mg, Na, P and pH decreased with soil depth and N concentration increased with soil depth. The biochar type had a significant effect ($p<0.05$) on soil Mg, Na and pH in the wet season. In the dry season, there were significant differences in soil K, Mg, P and pH. The study suggest that biochar applied at 10t/ha could be a potential in enhancing rape growth performance as well as improving soil physicochemical properties and can be of assistance to small scale farmers who have no access to expensive inorganic fertilisers.

Keywords: Biochar, organic, amendment, biomass

4.1 Introduction

Continuous use of land causes a decline in agricultural productivity due to mineral nutrient mining associated with high frequent cultivation and harvesting. The fertility of the soils can be improved by addition of organic and inorganic amendments (Mau and Utami 2014) but they do not last long in the soil. Therefore farmers can resort to using biochar which has potential to improve soil physical and chemical properties (Ventura *et al*. 2012; Wang *et al*. 2012; Vassilev *et al*. 2013), increase agricultural productivity (Jeffery *et al*. 2011) and mitigate the effects of climate change (Woolf *et al*. 2010; Gurwick *et al.* 2013; Van Zwieten *et al*. 2013). Furthermore, biochar application can directly add some macro and micro-nutrients to the soil (Gundale and DeLuca 2007; Major *et al*. 2010; Jones *et al*. 2012; Liu *et al*. 2012; Vassilev *et al*. 2013). Biochar is cheap to produce, lasts long in the soil and can be produced using locally available raw materials such as crop residues, thatch grass and manure. In some African countries such as Liberia, Guinea, Ghana and Sierra Leone, farmers used anthropogenic dark earths in gardening as well as in agro forestry to improve yields and maintain soil quality (Leach *et al.* 2012). In Kenya, Torres (2011) showed that charring biomass greatly improved soil nutrient status in degraded soils and improved maize productivity although more studies on optimal application rates were needed. Maize productivity was increased after biochar application in Zambian sandy soils whereas there were no effects on nutrient rich clayey soils (Cornelissen *et al.* 2013). In this regard, biochars have great potential to improve crop productivity especially in communal areas of Zimbabwe where soils are mainly sandy (Nyamangara *et al*. 2013).

Biochars from plant material are good soil conditioners while biochar from manure and compost are both conditioners and have a high nutrient content (Gundale and DeLuca 2006; Major *et al.* 2010; Uchiminya *et al*. 2010). Soil pH, electrical conductivity, and cation exchange capacity also increase after biochar amendment (Liang *et al*. 2006; Gundale and DeLuca 2007; Warnock *et al*. 2007; Amonette and Joseph 2009; Chan *et al*. 2009; Joseph *et al*. 2010). The increase in soil pH after biochar amendment results in increased solubility of some nutrients (N, P, Ca, Mg) making them available to plants (Atkinson *et al*. 2010), while reducing the availability of some toxic minerals e.g. Al (Sierra *et al*. 2003; Steiner *et al.* 2008). Amendment of soil with biochar also alters bulk density, water holding capacity and surface area of soils (Glaser *et al*. 2002; Texeira and Martins 2003; Asai *et al*. 2009; Abel *et al*. 2013; Lei and Zhang 2013) and improves root penetration (Chan *et al*. 2007). The combined effects of improved soil chemical and physical parameters lead to improved plant growth (Novotny *et al*. 2009). Addition of biochar also leads to a reduction in nitrogen leaching (Brockhoff *et al.* 2010; Guerena *et al*. 2012; Major *et al*. 2012) due to increased absorption and adsorption as well as water retention after biochar amendment (Kanthle *et al*. 2016). The levels of nutrients in the biochar depend on the levels of nutrients in the feedstock (Alexis *et al*. 2007) and losses that occur during pyrolysis.

Most smallholder farmers have limited access to inorganic fertilisers (Mvumi 2013) and an alternative option to improve soil fertility is through the use of amendments such as biochar. Gwenzi *et al.* (2015) evaluated effects of feedstocks used for biochar production in Zimbabwe and did not come up with conclusive results. In Zimbabwe, there is limited documentation on the effects of different feedstocks used to produce biochar on crop growth performance. In this study, the growth and productivity of *B. napus* was assessed in wet and dry seasons after application of four types of biochar amendments.

4.2 Materials and Methods

4.2.1 Study area

A detailed description of the study site was given in section 3.1.

4.2.2 Production of biochar and experimental procedure

Detailed descriptions on the production of biochar, experimental procedure and assessment of plant growth were given in sections 3.2, 3.3 and 3.4 respectively.

4.2.3 Soil sampling and analyses

A detailed description on soil sampling and analysis is given in section 3.5.

4.2.4 Statistical analyses

Statistical analysis was performed using Genstat (version 14.1). Data for yields were subjected to ANOVA to compare treatment means at $p<0.05$. Data were analysed according to the following model:

$$Yij = U + Bi + Sj + (B*S)ij + eij$$

4.3 Results

4.3.1 Nutrient content of biomass and biochar

Mg and N were lost during pyrolysis as shown by the reduced levels of these nutrients in the biochar (Table 4.1).

Table 4.1. Nutrient content of biomass used to produce biochar and the nutrient content of biomass after pyrolysis.

		Nutrient content (%)						
		C	Ca	K	Mg	N	Na	P
Pine sawdust	Biomass	68^{g}	0.18^{e}	0.14^{b}	0.16^{c}	0.17^{c}	0.04^{b}	11.00^{a}
	Biochar	72^{h}	0.15^{d}	0.16^{c}	0.14^{a}	0.06^{a}	0.04^{b}	13.30^{c}
H. filiphendula	Biomass	60^{c}	0.18^{e}	0.13^{a}	0.19^{e}	0.27^{d}	0.03^{a}	15.55^{e}
	Biochar	66^{f}	0.09^{a}	0.2^{d}	0.17^{d}	0.1^{b}	0.03^{a}	23.32^{f}
Maize stover	Biomass	59^{b}	0.11^{b}	0.84^{e}	0.53^{h}	0.8^{f}	0.04^{b}	12.34^{b}
	Biochar	62^{e}	0.5^{g}	1.56^{g}	0.34^{g}	0.7^{e}	0.04^{b}	23.41^{g}
Soya bean stover	Biomass	57^{a}	0.14^{c}	1.49^{f}	0.24^{f}	1.14^{g}	0.03^{a}	13.71^{d}
	Biochar	61^{d}	0.24^{f}	4^{h}	0.15^{b}	1.28^{h}	0.04^{b}	30.01^{h}
P value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
s.e.d		0.29	0.003	0.0003	0.003	0.003	0.0003	0.03
cv%		0.6	1.3	0.0	1.5	0.6	1	0.2

The results showed that soya bean biochar contained significantly ($p<0.05$) more nutrients compared to unpyrolysed stover with respect to P, C, Ca, K, and Na (Table 4.1). Generally, soya bean stover contained more K, N and P compared to the rest of the stover.

4.3.2 Effects of biochar feedstocks on growth of B. napus

There were no significant differences in *B. napus* yields from weekly harvests during both the wet and the dry season. However, the overall fresh weight yields of *B. napus* during the wet season were significantly higher ($p<0.05$) in all biochar amended plots than the control, except for maize stover biochar which was not significantly different ($p>0.05$) from the control. (Fig 4.1).

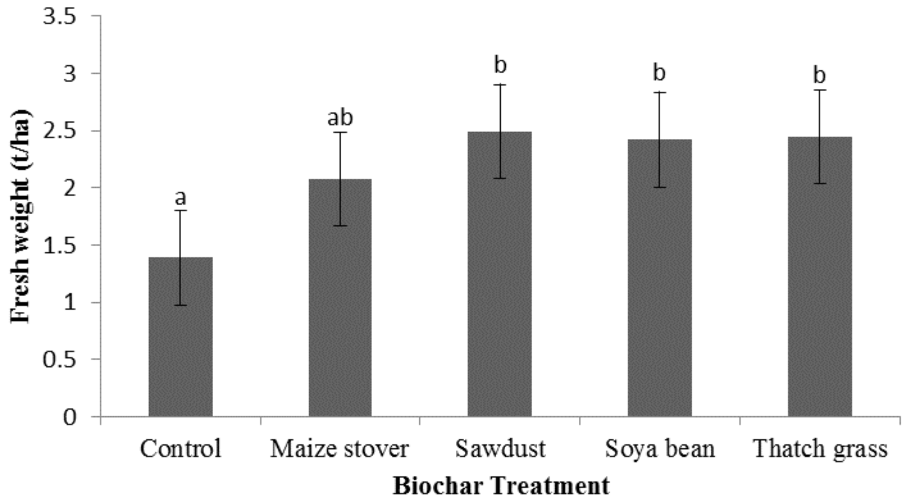

Fig 4.1 Mean *B. napus* fresh weight yield in treatments amended with biochar at 10 t/ha in the wet season.

In the dry season, the fresh weight yield followed the same trend as in the wet season with significantly higher ($p<0.05$) yields of *B. napus* in biochar amendments than control. All the biochar treatments were significantly higher ($p<0.05$) than the control (Fig 4.2).

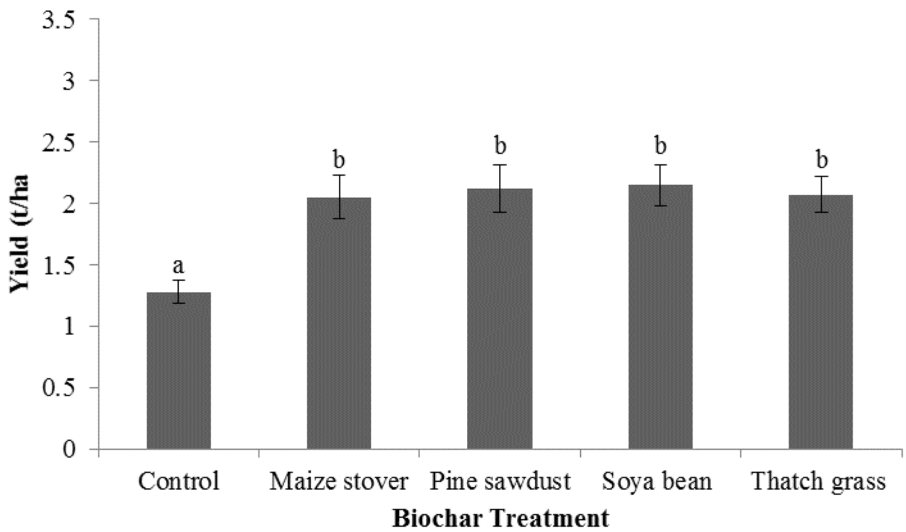

Fig 4.2 *B. napus* fresh weight yield in treatments amended with biochar at 10 t/ha in the dry season.

With respect to yield, all the biochar treatments gave significantly higher ($p<0.05$) *B. napus* yield compared to the control. The different types of biochar were however not different from one another (Fig 4.2). Biochar amended plots had significantly longer leaves than the control, with soya bean stover biochar and maize stover biochar giving the longest leaves followed by pine sawdust biochar and thatch grass biochar (Fig 4.3).

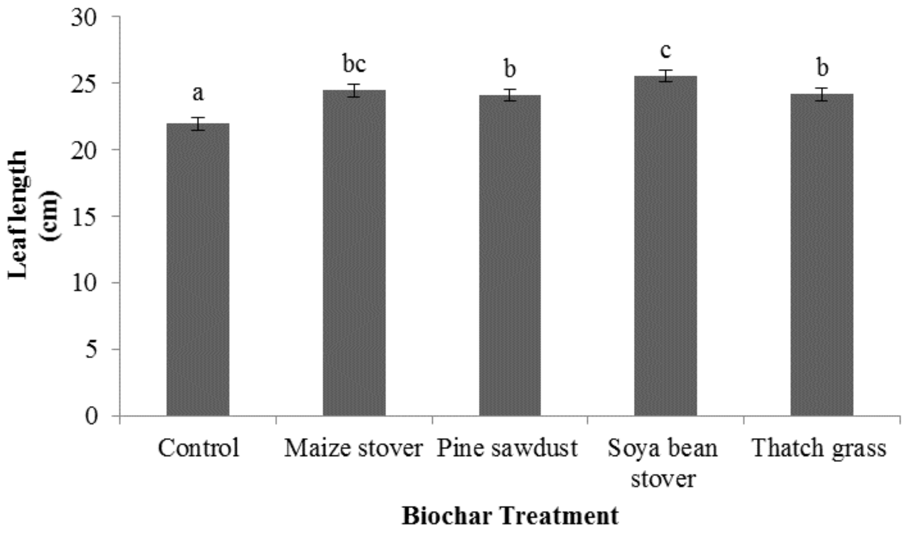

Fig 4.3 *B. napus* leaf length in the plots amended with biochar at 10 t/ha.

Maize stover and soya bean stover biochar maintained their superiority with respect to leaf area compared to pine sawdust and thatch grass biochar (Fig 4.4).

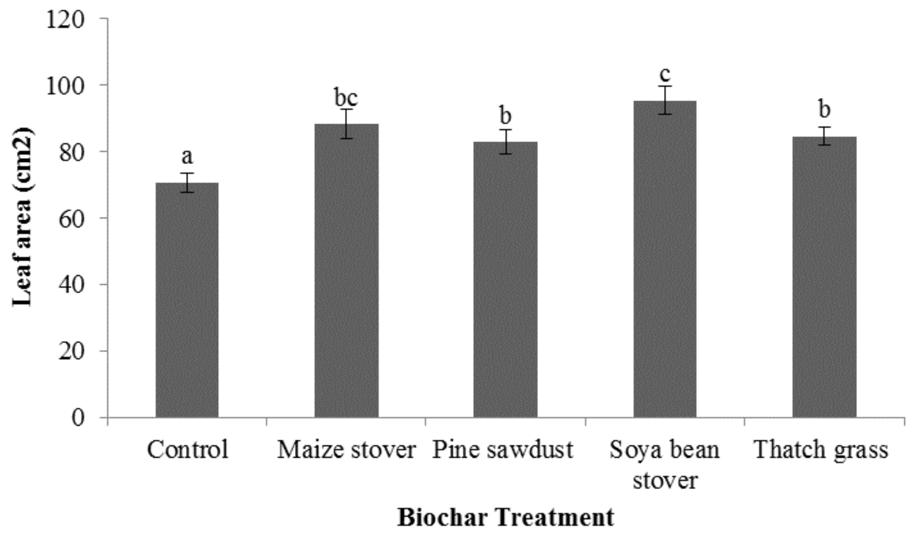

Fig 4.4 *B. napus* leaf area in the plots amended with biochar at 10 t/ha.

4.3.3 Effects of biochar feedstocks on moisture content of B. napus

Moisture content was significantly higher ($p<0.05$) in biochar treated plots than the control in both the wet and the dry season (Fig 4.7). Plots amended with maize stover biochar had the highest moisture content in the dry season compared to other biochar treatments and control. The control plots recorded the lowest moisture content in both the wet and the dry season.

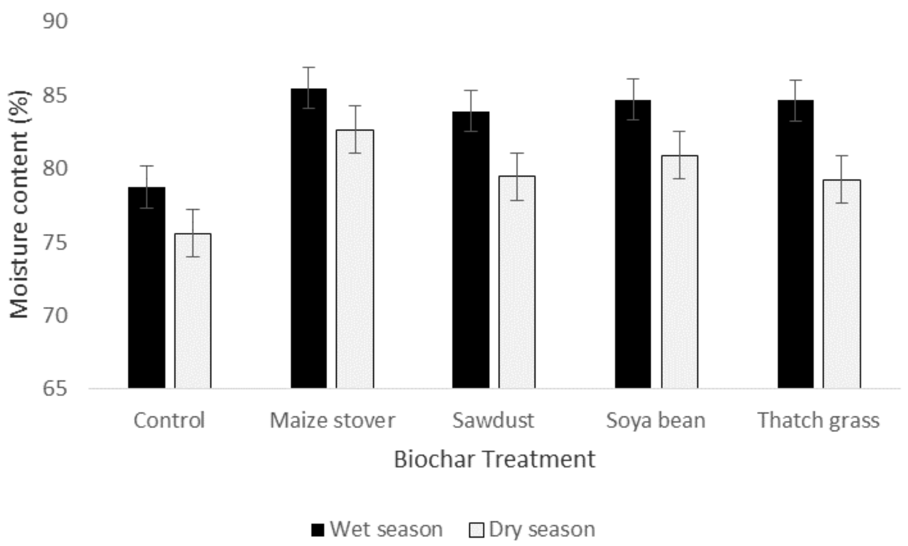

Fig 4.5 *B. napus* moisture content in the plots amended with biochar at 10 t/ha.

4.3.4 Effects of biochar on soil chemical properties

Biochar application resulted to a significant effect on soil chemical properties in different soil depths in the wet and dry season. The concentration of the C, Ca, Mg, Na and P decreased with soil depth and N concentration increased with soil depth (Table 4.2). Soil C, Ca, K, Mg, Na, P and pH generally increased in the dry season whilst soil N content decreased in the dry season in all the sampling depths.

Table 4.2: Effects of sampling depth on soil C, Ca, K, Mg, N, Na, P and pH after biochar application.

Soil chemical properties (%)		**Sampling depth (cm)**					
		0-10	10-20	20-30	P value	s.e.d	Cv%
C	Wet season	1.621[b]	1.251[ab]	0.892[a]	0.009	0.219	47.8
	Dry season	2.787[b]	2.459[b]	1.089[a]	<0.001	0.220	28.6
Ca	Wet season	0.957[c]	0.879[b]	0.732[a]	<0.001	0.029	9.2
	Dry season	1.266[b]	0.728[a]	0.655[a]	<0.001	0.045	14
K	Wet season	0.041[b]	0.034[a]	0.031[a]	0.014	0.003	27.1
	Dry season	0.081[b]	0.08[b]	0.06[a]	<0.001	0.004	15.4
Mg	Wet season	0.245[c]	0.181[b]	0.101[a]	<0.001	0.017	27.2
	Dry season	0.702[b]	0.28[a]	0.282[a]	<0.001	0.014	9.3
N	Wet season	13.45[a]	16.28[a]	24.87[b]	0.004	2.505	31.17
	Dry season	11.28[a]	12.74[a]	19.61[b]	<0.001	1.485	23
Na	Wet season	0.127[c]	0.047[a]	0.057[b]	<0.001	0.004	12.5
	Dry season	0.149[b]	0.083[a]	0.080[a]	<0.001	0.004	11
P	Wet season	20.08[c]	17.09[b]	12.08[a]	<0.001	0.922	15.4
	Dry season	23.98[c]	19.36[b]	12.39[a]	<0.001	0.965	14.2
pH	Wet season	6.9[c]	6.5[b]	6.1[a]	<0.001	0.154	6.5
	Dry season	7.2	7.1	6.9	>0.05	NS	6.3

The biochar type had a significant effect ($p<0.05$) on soil Mg, Na and pH in the wet season. In the dry season, there were significant differences in soil K, Mg, P and pH (Table 4.3). The soil chemical properties were generally high in the wet season than the dry season. Of all the treatments, the control had the least soil chemical properties.

Table 4.3: Effects of biochar type on soil K, Mg, Na, P and pH.

	Soil chemical properties (%)									
Biochar type	K		Mg		Na		P		pH	
	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season
Thatch grass	0.036	0.076[bc]	0.210[b]	0.415[ab]	0.079[b]	0.111	15.48	19.04[b]	6.6[b]	7.4[b]
Soya bean stover	0.038	0.083[c]	0.175[ab]	0.446[b]	0.078[b]	0.104	18.19	19.73[b]	7.1[c]	7.7[b]
Sawdust	0.039	0.069[ab]	0.183[b]	0.429[b]	0.086[b]	0.107	16.91	18.19[b]	6.8[bc]	7.5[b]
Maize stover	0.035	0.083[c]	0.179[b]	0.433[b]	0.079[b]	0.102	16.78	20.31[b]	6.6[b]	7.4[b]
Control	0.028	0.065[a]	0.131[a]	0.384[a]	0.063[a]	0.096	14.74	15.61[a]	5.4[a]	5.5[a]
P value	>0.05	0.007	0.027	0.023	<0.001	>0.05	>0.05	0.007	<0.001	<0.001
s.e.d	NS	0.005	0.023	0.018	0.005	NS	NS	1.246	0.199	0.212
cv%	27.1	15.4	27.2	9.3	12.5	11	15.4	14.2	6.5	6.3

There was a significant interaction ($p<0.05$) of biochar type and sampling depth on soil Na in the wet season (Fig 4.6). The results indicated that both biochar type and soil sampling depth influenced soil Na. Soil Na content was highest in sawdust biochar treatments at the 0-10 cm sampling depth compared to the rest of the treatments. There were no significant differences ($p>0.01$) for the 10-20 cm depths (Fig 4.6).

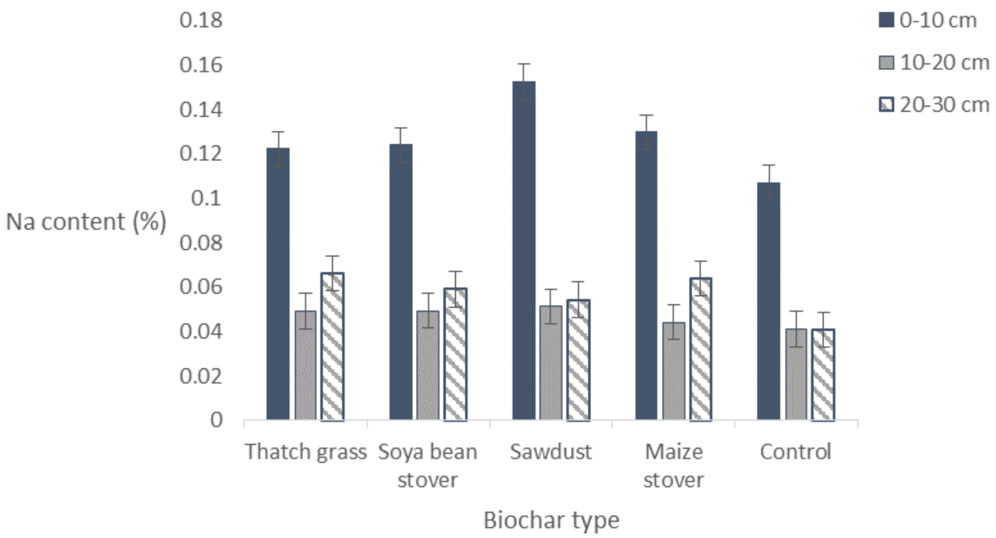

Fig 4.6 Interaction of biochar type and soil sampling depth on soil Na content in the wet season.

4.3.5 Effects of biochar feedstocks on soil physical properties

A significant ($p<0.05$) reduction in soil bulk density was noted following the addition of biochar in the wet and dry season. Soil bulk density was lower in the dry season than the wet season (Table 4.4).

Table 4.4: Effects of biochar type and sampling depths on soil bulk density and water holding capacity

Soil physical properties				
Biochar type	BD (g/cm^3)		WHC (%)	
	Wet season	Dry season	Wet season	Dry season
Thatch grass	1.03^a	1.01^b	47.5	46.3
Soya bean stover	1.03^a	0.95^a	49.3	45.1
Sawdust	1.05^{ab}	1.02^b	41.7	43.1
Maize stover	1.06^b	0.99^{ab}	46.5	48.1
Control	1.17^c	1.04^b	47.8	48
P value	<0.001	<0.001	>0.05	>0.05
s.e.d	0.01	0.02	NS	NS
cv%	1.5	4.2	17	10.7
Soil physical properties				
Sampling depth (cm)	BD (g/cm^3)		WHC (%)	
	Wet season	Dry season	Wet season	Dry season
0-10	0.96^a	0.87^a	51.1^b	50.35^b
10-20	1.07^b	0.99^b	47.2^b	47.11^b
20-30	1.17^c	1.16^c	41.3^a	40.88^a
P value	0.001	<0.001	0.007	<0.01
s.e.d	0.01	0.02	2.88	1.80
cv%	1.5	4.2	17	10.7

Biochar application did not have a significant effect on water holding capacity in both the wet and the dry season. Soil sampling depth had a significant effect on soil bulk density and water holding capacity after biochar application in both the wet and the dry season. Soil bulk density increased with sampling depth whilst soil water holding capacity decreased with sampling depth (Table 4.4).

Biochar amendment led to a significant interaction of biochar type and soil sampling depth on soil bulk density in the dry season (Fig 4.7). The 0-10 cm layer had significantly lower bulk density than the 20-30cm layer. In thatch grass and sawdust biochar treatments, bulk density in 0-10cm depth was significantly lower than the 10-20 cm depth.

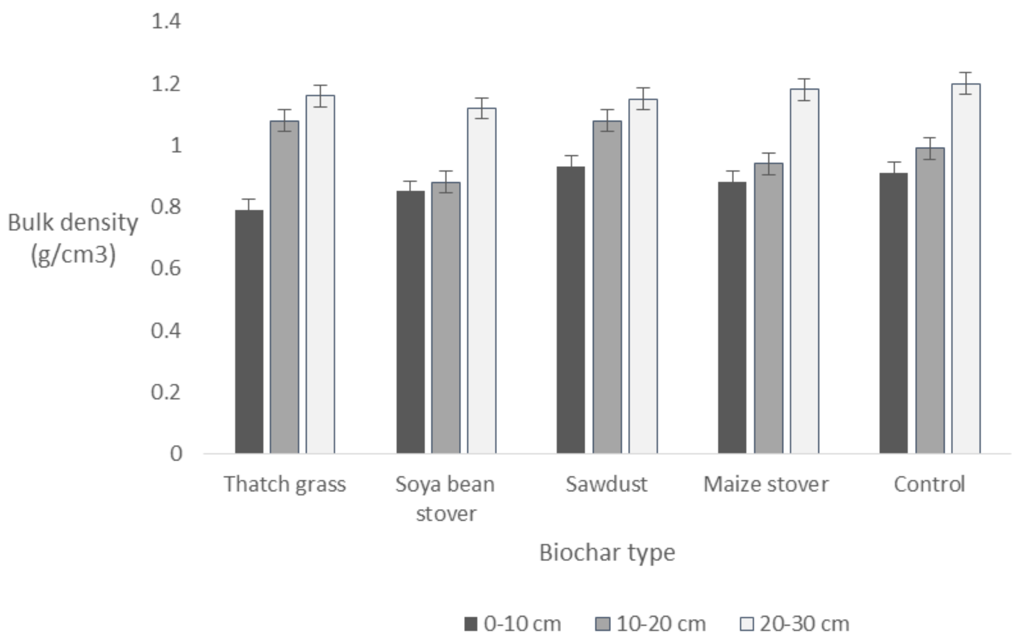

Fig 4.7 Interaction of biochar type and soil sampling depth on soil bulk density

4.4 Discussion

4.4.1 Effects of biochar feedstocks on growth of B. napus

Addition of biochar was beneficial for improving the growth of *B. napus* possibly due to increased soil pH. Considering the low soil pH before biochar application, it could be a possibility that improvement in yield was caused by an increase in the soil pH. Increasing soil pH enhances mineralisation hence improved nutrient availability for plant uptake (Schulz and Glaser 2012). Biochar application led to a significant decrease in soil bulk density, which enhances root development and growth (Asai *et al.* 2009; Chan *et al.* 2008) thereby increasing the growth performance of *B. napus,* as evidenced by longer and wider leaves in biochar treatments compared to the control. Similarly, Graber *et al.* (2010) found significantly high leaf length and leaf area of tomato and pepper after biochar application. Biochar amended plots retained more moisture thus more water was available for plant uptake leading to a higher moisture content of *B. napus.* Improvement in plant performance after biochar amendment have also been reported in field and controlled experiments elsewhere (Laird *et al*. 2009; Van Zwieten *et al*. 2009; Carter *et al*. 2013; Biederman and Harpole 2013; Paz Ferreiro *et al.* 2014; Alberquerque *et al*. 2014; Haider *et al.* 2014; Jaiswal *et al.* 2014; Macdonald *et al*. 2014; Xu *et al.* 2014; Viger *et al.* 2015). Wheat straw biochar significantly improved *B. napus* L biomass yield (Ahmed and Schoenau 2015). A study by Liu and Huang (2013) reported improved rapeseed growth after biochar addition to upland red soil. The effects of biochar on plant growth depend on the soil type (Macdonald *et al*. 2014) and the biochar type (Ahmed and Schoenau 2015). The yield in this study decreased in the dry season. Carter *et al.* (2013) also found that yield of lettuce and cabbage after biochar amendment decreased in the second crop cycle and further decreased in the third crop cycle due to depletion of nutrients.

4.4.2 Effects of biochar from different feedstocks on soil chemical properties

Biochar amendment significantly increased soil pH (Table 4.3). Soil pH was generally higher in plots amended with soya bean stover biochar than other biochar types. This is because leguminous plants accumulate more bases in their biomass during their growth due to unbalanced absorption of cations and anions as compared to non-leguminous plants (Yan and Schubert 2000). When the soya bean stover biochar was incorporated into the soil, its high alkalinity led to a higher soil pH as compared to other biochar types. The increased pH may also be due to ash retained onto biochar (Nigussie *et al.* 2012) which is rich in cationic elements. These results agree with other studies that showed a significant increase in soil pH after biochar amendment (Peng *et al.* 2011; Zhang *et al*. 2011; Borchard *et al*. 2012; Deal *et al*. 2012; Schulz and Glaser 2012; Paz-Ferreiro *et al.* 2014; Alberquerque *et al*. 2015). Rondon *et al*. (2007) also reported an increase in soil pH after biochar amendment due to the liming effect of the ash in the biochar. Kannan Pandian *et al*. (2016) also reported an increase of pH from 5.7 to 6.3 after biochar was added at a rate of $5t/ha^{-1}$. However, Brewer *et al*.

(2012) found no significant difference in soil pH after biochar application on calcareous soils, where the pH was already high.

Generally, the amount of C, Ca, K, Mg, Na and P were highly concentrated in the 0-10 cm depth. This is mainly because the biochar could not be evenly distributed into the soil upto the 20-30cm depth. Moreover, biochar is less dense and hence it floated on the water during irrigation and thus the high concentration in the 0-10 cm depth. Increased amounts of Ca, K, Mg Na and P was mainly due to increased concentrations of these elements in soil solution. Soil organic C was improved by biochar application in the 0-10 cm mainly because biochar is a highly carbonaceous material. A study by Trupiano *et al*. (2017) also found increased soil total organic C after biochar application due to improved C accumulation and sequestration. Mensah and Frimpong (2018) also found significant increases in soil organic C after biochar amendment. However, for mineral N, there was evidence of leaching shown by significantly high amount of mineral N in the 20-30 cm depth.

Biochar type had significant effect on soil available K, Mg, Na and P. This increase could be due to improved pH which leads to improved availability of base cations (Schulz and Glaser 2012). Biochar supplies a number of soil nutrients. Complex reactions of biochar and the soil unleashes soil nutrients in available form for plant uptake (Bista *et al*. 2019). The availability of these nutrients increases with increased soil pH which reduce Al and Fe toxicity Mensah and Frimpong 2018). Soil pH in this study increased by more than one unit, thus making soil base cations available for plant uptake and eventually improving plant growth performance. Soil available K was highest in maize stover biochar and soya bean stover biochar treatments. Soil K content varies with the amount of K present in the biochar type (Miller *et al.* 2013). Soya bean stover had the highest amount of K (4%) followed by maize stover biochar with 1.56%.

Biochar type did not have a significant effect on soil mineral N and this was simultaneous with improved plant performance and improved leaf length and leaf area of *B. napus*. This could be due to depletion of the N due to uptake (Bista *et al*. 2019) by the *B. napus.*

4.4.3 Effects of biochar from different feedstocks on soil physical properties

Biochar amendment significantly reduced the soil bulk density of the soil in both the wet and the dry season, with the lowest bulk density found in the plots amended with thatch grass biochar and soya bean stover biochar in both the wet and the dry season. The reduction in the soil bulk density of the soil may be attributed to the low BD of the biochar (Downie *et al*. 2009). Similarly, Zhang *et al*. (2011) and Alberquerque *et al*. (2014) found a significant decrease in the soil bulk density after biochar amendment. In other studies, biochar amendment in sandy soils caused a reduction in soil bulk density (Downie *et al*. 2009; Laird *et al*. 2010; Basso *et al.* 2012).

There were no significant differences in soil WHC among biochar types in both wet and the dry season. In support of this, Major *et al.* (2010) showed that addition of biochar to clayey soils did not affect soil WHC. Even in some sandy soils, biochar application did not have any significant effect (Borchard *et al*. 2012).

Soil sampling depth significantly increased soil water holding capacity and reduced soil bulk density after biochar application in the wet and the dry season. The 0-10 cm depth had the highest water holding capacity and the least soil bulk density mainly because biochar was mainly concentrated in the 0-10 cm depth. Biochar have a low bulk density which results in more pore space for water retention (Alburquerque *et al.* 2015). Therefore biochar can be used to reduce water stress thereby increasing crop growth performance in semi-arid areas. Sun *et al.* (2014) reported an increase in the soil available water content after biochar amendment. Karhu *et al*. (2011) also found increased WHC after biochar application.

Moreover, reduced soil bulk density due to biochar addition helps in promoting root growth (Atkinson *et al.* 2010). This should have caused improved growth performance of *B. napus* by enhancing root growth and development. This shows that with continued application, biochar has a potential to increase the WHC of soils. Basso *et al*. (2012) found higher WHC at 0-10 cm and 10-20 cm layers than the 20-30 cm layer and attributed the differences to the presence of biochar in the top two depths.

4.5 Conclusion

The yields of *B. napus* after biochar amendment were significantly improved. Leaf length and leaf area and moisture content in biochar amended plots were significantly higher than the control. The improvement in the growth performance of *B. napus* was attributed to the significantly higher content of Ca, K, Mg, Na, P, soil pH, soil bulk density and water holding capacity mainly in the 0-10cm depth which is the effective rooting zone for *B. napus*. Increase in soil pH causes the soil nutrients to be readily available for plant uptake. Soil organic C increased in the 0-10cm depth. Soil mineral N was significantly low in the 0-10 cm and high in the 20-30 cm showing evidence of leaching. Biochar amendment may be a sustainable tool for agricultural production in smallholder farming systems of Zimbabwe since the biochar feedstocks are readily available. More research should be done over periods greater than one year and in different soil types at different application rates.

CHAPTER 5

5.0 Effects of biochar application rates on soil physical and chemical properties and the performance of rape (*Brassica napus)*

Abstract

The use of biochar can be considered a cheap option to improve soil physical, chemical properties and plant growth. This study analysed the effects of biochar from maize *(Zea mays)* stover, soya bean (*Glycine max)* stover and thatch grass (*Hypharrenia filipendula)* on soil physical, chemical properties and growth of *Brassica napus* (*B. napus).* Biochar was applied at rates of 5, 10, 15 and 20 t/ha using a 3x4x3 factorial experiment in a randomised complete block design (RCBD) with three replicates. *Brassica napus* was grown in the wet season and dry season of 2015 at Glen Avilin Farm in Shamva district, Zimbabwe. Harvesting started four weeks after transplanting. The crop was harvested weekly for four weeks and thereafter fortnightly and assessed for yield (fresh weight), moisture content, leaf length and leaf area over a growth period of two months. The soil samples were collected before biochar application, after the first crop (wet season) and after the second crop (dry season) and were analysed for carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), Magnesium (Mg), sodium (Na), pH, water holding capacity and bulk density. Biochar application rate led to a significantly high ($p<0.05$) fresh weight yield, leaf length, leaf area and moisture content of *B. napus*. In both the wet and the dry season, biochar application rate of 20 t/ha had the highest yield, leaf length and leaf area of *B. napus* across all the biochar types. There were significant interaction ($p<0.05$) between biochar type and application rate on leaf length and leaf area of *B. napus*. Nutrient content was significantly high ($p<0.05$) in the 0-10 cm depth in the wet and dry season. The 10t/ha application rate recorded the highest amounts of soil Mg and pH. Soil P content was highest in the 20t/ha application rate. Soil sampling depth had a significant effect on bulk density and water holding capacity. Water holding capacity was significantly high ($p<0.05$) in biochar application rate of 20t/ha in the dry season. The higher the application rate, the lower the soil bulk density. The results showed that *B. napus* yield is most closely related with biochar application rate. However, long term studies on biochar application could give best results.

Keywords: Feedstocks, soil amendment, water holding capacity, bulk density

5.1 Introduction

Nutrient depetion is threatening food security and agricultural productivity in the Sub-Saharan Africa (SSA) region (Diagana 2003). Asenso-Okyere and Jemaneh (2012) showed that a large percentage of SSA dry land is not suitable for crop production because of low organic matter content and water holding capacity. A large population that depend on agricultural productivity are being affected by land degradation and measures should be put in place to improve agricultural productivity (Yilangai *et al*. 2014). Like any other SSA soil, Zimbabwean soils are highly degraded and efforts should be made to improve soil nutrient retention thereby improving agricultural productivity. An option may be the use of inorganic fertilisers. However, inorganic fertilisers emit greenhouse gases (Filiberto and Gaunt 2013) and they are also expensive to most smallholder farmers (Mvumi 2013). The use of biochar can be considered a cheaper option to improve soil physical and chemical properties as well as plant growth (Glaser *et al*. 2002; Bird *et al*. 2011; Brantley *et al*. 2015). Biochar amendment increases soil pH (Yuan and Xu 2011; Deal *et al*. 2012), thereby improving soil microbial habitat (Gaskin *et al*. 2008; Kwapinski *et al*. 2010). Biochar also increases soil water holding capacity (Novak *et al*. 2009), increases the levels of organic carbon in the soil (Kwapinski *et al*. 2010; McHenry 2011), reduces leaching of soil nutrients (Ding *et al*. 2010; Taghizadeh-Toosi *et al* 2011) and the rate of improvement depend on feedstock type and application rate (Novak *et al*. 2009). Different application rates have been used in different studies yielding different results. However, there is no study that has evaluated varying application rates of different biochars in order to obtain the optimal application rates suitable for local conditions. This study therefore assessed the effects of biochar type, and biochar application rate on selected soil chemical and physical properties as well as the growth of *B. napus*.

5.2 Materials and methods

5.2.1 Study area

A detailed description of the study site was given in section 3.1.

5.2.2 Production of biochar and experimental procedure

Detailed descriptions of biochar production and experimental procedure were given in sections 3.2 and 3.3 respectively.

5.2.3 Soil sampling and analyses

A detailed description of soil analysis was given in section 3.5.

5.2.4 Assessment of plant growth

A detailed description on the assessment of plant growth was given in section 3.4.

5.3 Statistical analysis

Statistical analysis was performed using Genstat (version 14.1). Data were subjected to ANOVA for 3X4 factorial and treatment means were separated using least significant difference (LSD) at $p<0.05$. Data were analysed according to the following model:

$$Yijk = U + Ti + Rj + Dk + (T*R)ij + (T*D)ik + (R*D)jk + (T*R*D)ijk + eijk$$

5.4 Results

5.4.1 Effects of biochar application rates on growth performance of B. napus

The application rate had a significant effect ($p<0.05$) on *B. napus* fresh yield and moisture content in both the wet and the dry season (Table 6.1) with the application rate of 20 t/ha having the highest yield and moisture content in both seasons. Biochar type had no significant effect in yield and moisture content in the wet and the dry season.

Table 5.1 Effects of biochar application rates on *B. napus* yield and moisture content.

	Wet season	**Dry season**
Rate (t/ha)	Moisture content (%)	Moisture content (%)
5	86.3^{a}	82.3^{a}
10	87.7^{ab}	82.4^{a}
15	88.1^{ab}	84.8^{b}
20	89^{b}	86.6^{b}
P value	0.005	<0.001
s.e.d	1.28	0.9
cv%	4.6	5.1

There is a strong positive correlation between the application rate and *B. napus* fresh yield as shown in Fig 5.1. As the biochar application rate increased, the *B. napus* fresh yield also increased.

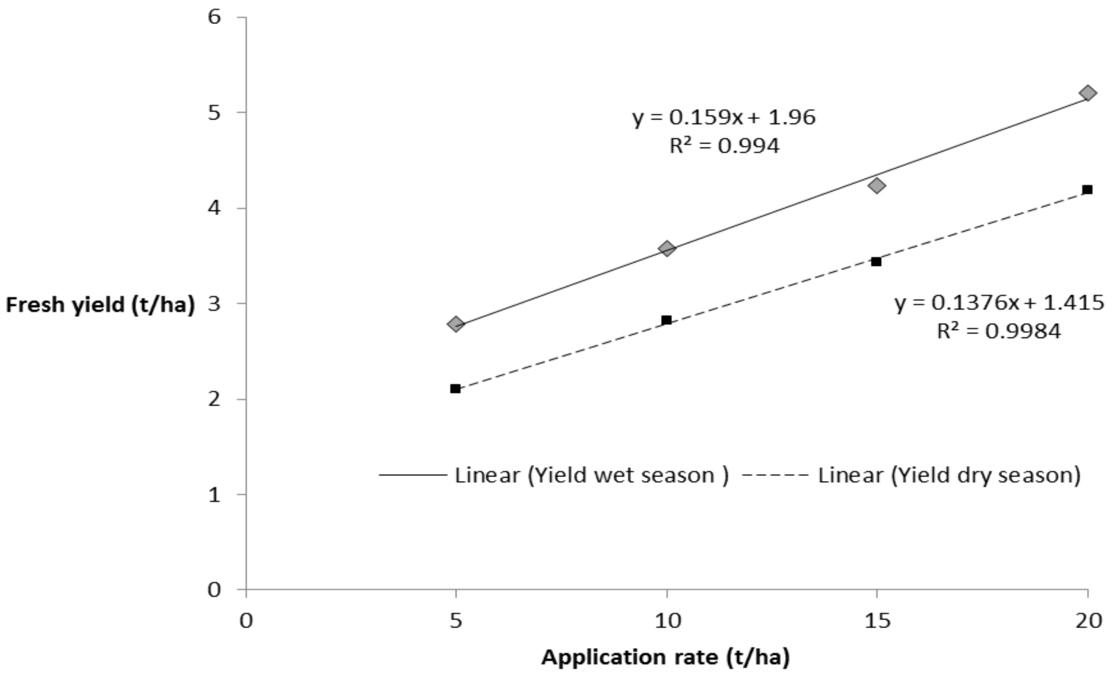

Fig 5.1: *B. napus* fresh yield after biochar amendment in the wet and dry season

There were no significant interactions of biochar type and application rate on *B. napus* fresh yield and moisture content in the wet and dry seasons.

There was a significant effect ($p<0.05$) of application rate on leaf length and leaf area of *B. napus*. The 20t/ha application rate gave the highest leaf length and leaf area (Table 5.2). Generally, *B. napus* leaf length and leaf area were not significantly improved ($p>0.05$) by biochar types.

Table 5.2: Effects of biochar application rates on B. *napus* leaf length and leaf area

Rate (t/ha)	**Leaf length (cm)**	**Leaf area (cm^2)**
5	26.6^{a}	77.8^{a}
10	28.7^{b}	87.8^{b}
15	29.9^{b}	92.6^{b}
20	31.5^{c}	118.6^{c}
P value	<0.001	<0.001
s.e.d	0.69	3.84
cv%	22.4	38.6

5.4.2 Effects of biochar application rates on soil chemical properties

Soil organic Carbon

Soil sampling depth had a significant effect ($p<0.05$) on soil organic C in the wet and dry season after biochar application (Table 5.3). Elevated amounts of soil organic C were in the 0-10 cm depth. In the dry season, there was a significant interaction ($p<0.05$) between the biochar application rate and soil sampling depth (Fig 5.2) with 15 t/ha and 20t/ha in the 0-10 cm having the highest soil organic C content. Biochar types and biochar application rates did not have a significant effect ($p>0.05$) in soil organic C.

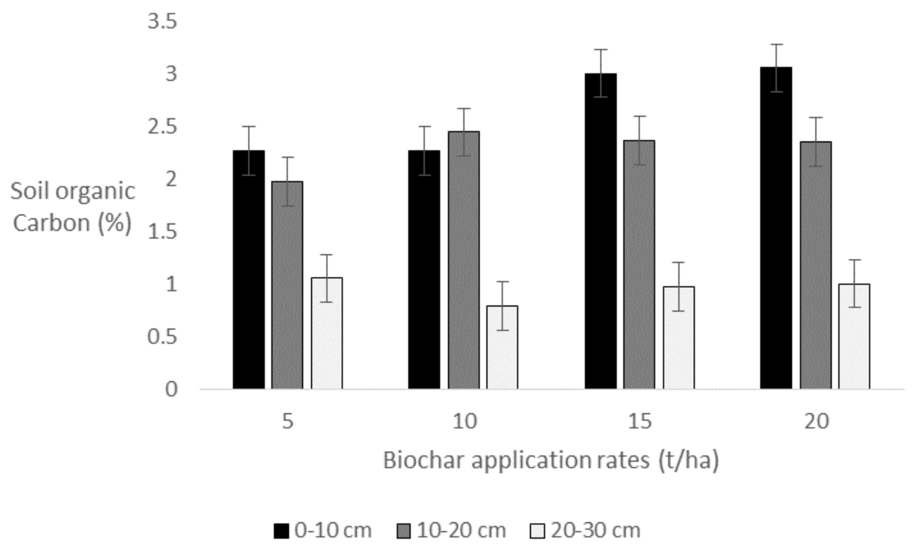

Fig 5.2: Interaction effect of biochar application rate and soil sampling depth on soil organic C content in the dry season.

Calcium

Soil sampling depth had a significant effect ($p<0.05$) on soil Ca content after biochar application in the wet and the dry season (Table 5.3). The 0-10 cm sampling depth had the highest soil Ca content and the dry season had more soil Ca in all the sampling depths. There were no significant effects ($p>0.05$) on the biochar type and biochar application rates to soil Ca content.

Table 5.3: Effects of sampling depths on soil C, Ca, K, Mg, N, Na, P and pH after biochar application.

Soil chemical properties (%)		Sampling depth (cm)					
		0-10	10-20	0-30	P value	s.e.d	cv%
C	Wet season	1.58[c]	1.01[b]	0.66[a]	<0.001	0.09	36.3
	Dry season	2.65[c]	2.29[b]	0.96[a]	<0.001	0.11	24.6
Ca	Wet season	1.8[c]	1.39[b]	0.96[a]	<0.001	0.17	51.9
	Dry season	2.87[c]	1.6[b]	0.9[a]	<0.001	0.26	60.5
K	Wet season	0.06[c]	0.03[b]	0.02[a]	<0.001	0.003	37.6
	Dry season	0.1[c]	0.09[b]	0.07[a]	<0.001	0.004	20.1
Mg	Wet season	0.41[c]	0.19[b]	0.15[a]	<0.001	0.03	48.6
	Dry season	0.93[c]	0.42[b]	0.27[a]	<0.001	0.05	41
N	Wet season	13.44[a]	17.17[b]	29.99[c]	<0.001	1.63	40.2
	Dry season	14.8	17	16.3	>0.05	NS	60
Na	Wet season	0.03[c]	0.02[b]	0.01[a]	<0.001	0.0006	12.4
	Dry season	0.14[c]	0.04[a]	0.05[b]	<0.001	0.003	17.9
P	Wet season	20.76[c]	17.01[b]	11.77[a]	<0.001	0.52	13.3
	Dry season	24.51[c]	19.87[b]	14.79[a]	<0.001	1.1	23.6
pH	Wet season	8[ab]	8.1[b]	7.8[a]	0.021	0.12	6.5
	Dry season	8.2[c]	7.8[b]	7.5[a]	<0.001	0.14	7.7

Potassium

Biochar type, application rate and soil sampling depth had a significant effect ($p<0.05$) on soil K. Soil K content decreased with soil sampling depth (Table 5.3). The higher the application rate, the higher the amount of soil K (Table 5.4). Soya bean stover biochar had significantly higher ($p<0.05$) K content than the other biochar types in the wet and dry season.

Table 5.4: Effects of biochar type and application rate on soil K content.

Biochar application rates (t/ha)	K content (%)	
	Wet season	Dry season
5	0.027[a]	0.076[a]
10	0.035[ab]	0.079[a]
15	0.04[bc]	0.098[b]
20	0.047[c]	0.1[b]
P value	<0.001	<0.001
s.e.d	0.004	0.005
cv%	37.6	20.1
Biochar type	**K content (%)**	
	Wet season	Dry season
Thatch grass biochar	0.031[a]	0.081[a]
Soya bean stover biochar	0.048[b]	0.098[b]
Maize stover biochar	0.034[a]	0.085[a]
P value	<0.001	<0.001
s.e.d	0.003	0.004
cv%	37.6	20.1

There was a significant interaction between biochar type and application rate on soil K content in the wet and dry season (Fig 5.3). This indicates that both the application rate and biochar type have an effect on soil K. Soya bean stover biochar applied at 20t/ha had the highest soil K content in the wet and dry season.

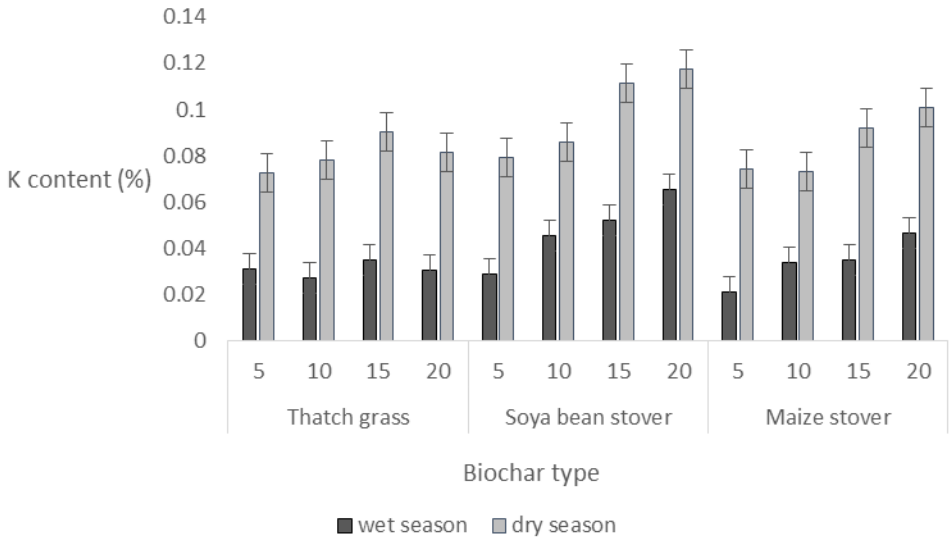

Fig 5.3 Interaction effect of biochar type and application rate on soil K content.

There was a significant interaction between biochar type and soil sampling depth on soil K content in the wet and dry season (Fig 5.4). Soya bean stover biochar in the 0-10 cm depth had the highest amount of soil K content in the wet and the dry season. The 20-30 cm depth had the least amount of soil K in the wet and dry season.

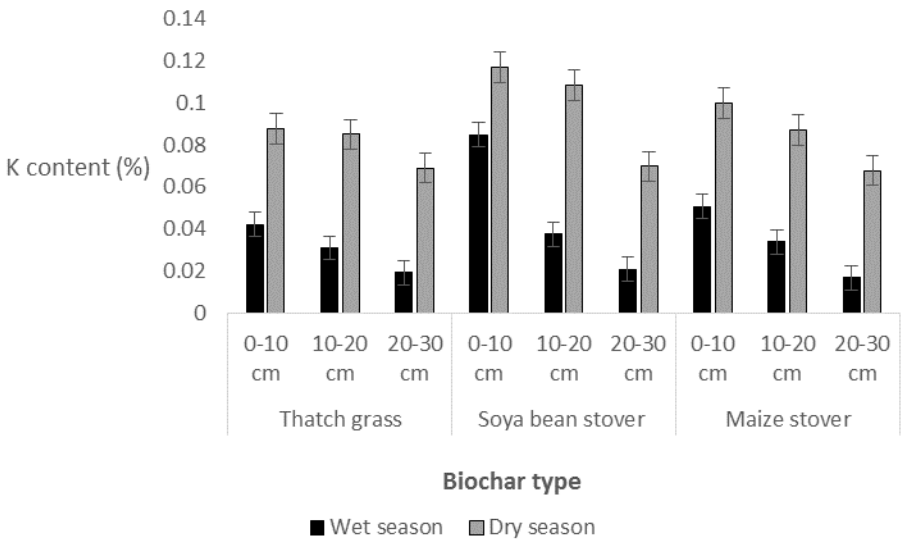

Fig 5.4: Interaction of biochar type and soil sampling depth on soil K content.

Magnesium

Following biochar application, biochar application rate and soil sampling depth had a significant effect ($p<0.05$) on soil Mg in the wet and the dry season (Table 5.5). Soil Mg content was highest in the 10t/ha application rate in both seasons. Generally, the dry season had more soil Mg content than the wet season.

Table 5.5: Effects of biochar application rates on soil Mg, mineral N, Na, P and pH.

Biochar application rates (t/ha)	**Mg (%)**		**Mineral N (ppm)**		**Na (%)**		**P (mg/kg)**		**pH**	
	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season
5	0.195[a]	0.46[a]	14.56[a]	13	0.02	0.078	15.23[a]	18.3	7.8	7.5[a]
10	0.285[b]	0.65[b]	20.34[c]	19.29	0.021	0.078	16.53[b]	19.83	8.1	8.1[b]
15	0.242[ab]	0.51[a]	15.23[ab]	14.85	0.021	0.082	16.44[b]	19.51	8	7.9[b]
20	0.282[b]	0.58[ab]	18.67[bc]	17	0.020	0.079	17.86[c]	21.25	7.9	7.8[ab]
P value	0.028	0.016	0.009	>0.05	>0.05	>0.05	<0.001	>0.05	>0.05	0.013
s.e.d	0.033	0.061	1.88	NS	NS	NS	0.6	NS	NS	0.16
cv%	48.6	41	40.2	60	12.4	17.9	13.3	23.6	6.5	7.7

Nitrogen

Soil mineral N was significantly affected ($p<0.05$) by biochar application rate and soil sampling depth in the wet season. Soil mineral N was highest in the 10t/ha application rate in the wet season (Table 5.5). The 0-10 cm sampling depth recorded the least mineral N content in the wet season (Table 5.3). However, there were no significant effects after biochar was added to the soil in the dry season.

Sodium

Soil sampling depth had a significant effect ($p<0.05$) on soil Na after biochar application in the wet and dry season (Table 5.3). Soil Na content was highest in the 0-10 cm depth in both seasons.

Phosphorus

There were significant differences ($p<0.05$) in soil P among the biochar application rates and soil sampling depths. Soil P content was significantly high in the 20 t/ha application rate (Table 5.5). There was a significant interaction between biochar type and application rate on soil P (Fig 5.5) in the wet season. Soya bean stover applied at 20t/ha outperformed all the other treatments.

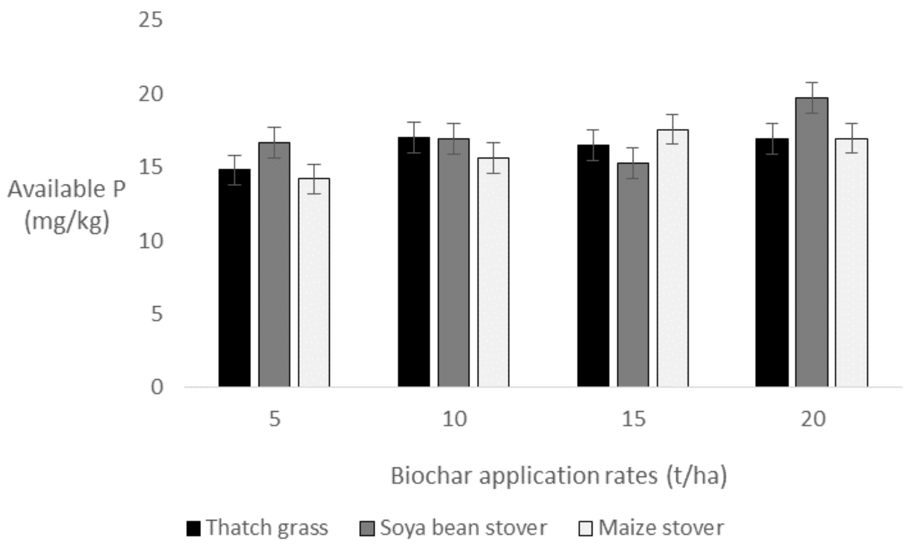

Fig 5.5: Interaction effect of biochar type and application rate on soil P.

pH

Generally, soil pH significantly decreased down the soil sampling depths after biochar application (Table 5.3). In the wet season, biochar applied at 10t/ha resulted in significantly higher ($p<0.05$) pH compared to other treatments (Table 5.5).

5.4.3 Effects of biochar application on soil physical properties

Soil bulky density (BD) was significantly decreased ($p<0.05$) after biochar treatment in the 0-10 cm layer in both the wet and the dry season. Moreover, bulk density decreased with increasing application rates with the highest application rate having the lowest BD (Table 5.6).

Table 5.6: Effects of biochar application rates and soil sampling depth on soil bulk density and water holding capacity.

Biochar application rates (t/ha)	**Bulk density (g/cm^3)**		**Water holding capacity (%)**	
	Wet season	Dry season	Wet season	Dry season
5	1.07[b]	1.06[b]	46.4	44.5[a]
10	1.06[b]	1.07[b]	47.3	48.4[b]
15	1.01[a]	1.03[ab]	49.2	49.3[b]
20	0.99[a]	0.98[a]	47.7	49.8[b]
P value	<0.001	0.009	>0.05	0.012
s.e.d	0.01	0.03	NS	1.7
cv%	3.5	9.9	19	13.2
Soil sampling depth	**Bulk density (g/cm^3)**		**Water holding capacity (%)**	
	Wet season	Dry season	Wet season	Dry season
0-10 cm	0.91[a]	0.84[a]	58.8[c]	58.2[c]
10-20 cm	1.04[b]	1.04[b]	47.8[b]	48.9[b]
20-30 cm	1.15[c]	1.23[c]	36.1[a]	36.9[a]
P value	<0.001	<0.001	<0.001	<0.001
s.e.d	0.01	0.02	2.1	1.5
cv%	3.5	9.9	19	32.2

Soil sampling depth had a significant effect ($p<0.05$) on water holding capacity after biochar application in the wet and dry season (Table 5.6). The 0-10 cm depth had significantly high water holding capacity. In the dry season, biochar application rates had a significant effect on water holding capacity, with the 20t/ha having the highest water holding capacity. There were generally no significant interactions on water holding capacity and bulk density.

5.5 Discussion

5.5.1 Effects of biochar application on growth performance of *B. napus*

The fresh weight yield of *B. napus* responded positively to the biochar application rates in both the wet and the dry season, with the highest application rate giving the highest yield. This could be due to direct addition of nutrients to the soil by the biochar. Improvement in the soil physical and chemical properties may have contributed to the improved yield, moisture content leaf length and leaf area of the *B. napus.* Biochar improves soil water holding capacity leading to a reduction in total leachate volume (Zheng *et al*. 2013) thereby making more nutrients available for plant uptake and eventually improved crop yield. The findings are similar to Carter *et al.* (2013) who reported increases in the above ground biomass of lettuce and cabbage after biochar amendments. Several studies have found improvements in plant performance after biochar amendments (Chan *et al.* 2007; Chan *et al.* 2008; Jeffery *et al.* 2011) and the higher the application rate the higher the crop biomass (Lehmann *et al.* 2006; Steiner *et al.* 2007; Van Zwieten *et al.* 2010; Kammann *et al.* 2012) due to concentrated cations in the biochar. This intensifies the available nutrients for plant uptake and eventually biomass accumulation (Trupiano *et al*. 2017). Other studies also show that crop productivity increase significantly with increased biochar application rates either when used alone (Yeboah *et al.* 2009), or together with other inorganic fertilisers (Arif *et al.* 2012). Reduced bulk density enhances root growth and thus improves plant growth (Asai *et al.* 2009; Chan *et al.* 2008).

Biochar application rates resulted in a significantly higher leaf length and leaf area of *B. napus* than the control. This can be attributed to a significant improvement in the mineral N content by biochar application rate and soil sampling depth. Nitrogen is an essential component of protein and improves metabolic processes which improve leaf size and subsequently vegetative growth of the *B. napus* (Leghari *et al*. 2016). Similarly, Carter *et al.*

(2013) found an increase in the stem length with an increase in biochar application. Graber *et al.* (2010) also found a significant increase in tomato and pepper leaf length and leaf area after biochar amendments.

5.5.1 Effects of biochar application rates on soil chemical properties

Biochar was concentrated mainly in the 0-10 cm depth and hence the higher nutrient content, pH and soil organic C in the 0-10 cm depth. Soil mineral N was significantly increased by biochar application rates and soil sampling depth in the wet season. Application rate of 10t/ha had the highest amount of N. High biochar application rates may lead to a higher C:N ratio which result to N immobilization. Ca, Mg and K were significantly improved after biochar application. This may be due to mineralisation which causes the release of these nutrients from organic matter (Fischer and Glaser 2012). Ash content in the biochar releases some exchangeable bases in the soil thereby increasing Ca, Na and K content for plant use. Schulz and Glaser (2012) also observed an increase in Na content after biochar amendment. Interactions and reactions of soil with biochar lead to increases in soil available K (Joseph *et al.* 2010). Other studies also reported an increase in available K after biochar amendment (McElligot 2011; Schulz and Glaser 2012; Brewer *et al.* 2012; Kelly *et al.* 2015) and attributed it to the ash content in the biochar as well as the increased surface area and porous nature of the biochar (Nigussie *et al*. 2012). A significant interaction of biochar type and application rate on K shows that both biochar type and application rates have an effect on soil K. The amount of K was highest in the soya bean stover biochar treatments applied at 20 t/ha. These results may have been influenced by the amount of K which was present in soya bean stover biochar (4%) (Table 5.1) and the higher the biochar application rate the more the K content available in the soil. Significant increases in soil P could be as a result of the high concentration of P in the soya bean biochar with the highest application rate (20t/ha) increasing the concentration of P in the soil. Low soil pH results in iron oxides adsorbing soil P on its surface. Increasing soil pH by biochar application neutralises the Fe and Al in the soil thus making P available for plant uptake (Cui *et al*. 2011). Increases in soil P content especially in the 0-10 cm depth could be due to adsorption of P on biochar surfaces, thereby reducing P leaching (Beck *et al*. 2011). Biochar has a high amount of carbon and hence the high SOC after biochar amendment (Liang *et al*. 2006; Solomon *et al*. 2007). However, Zhang *et al*. (2013) revealed that SOC increased with increased biochar application rates as also noted in this study.

5.5.2 Effects of biochar application rates on soil physical properties

Biochar amendment resulted in a significant decrease in soil bulk density (BD) and a significant increase in soil WHC in the wet and dry seasons and the higher the application rate, the lower the bulk density. This is due to the low particle density of biochar particles as reported by (Jones *et al*. 2010; Laird *et al*. 2010; Chen *et al*. 2011) thus increased pore spaces for retaining moisture which makes biochar helpful in reducing water stress and improve plant productivity in low rainfall areas (Kammann *et al* 2011.). Biochar application leads to improved soil aggregation and aeration thus lowering soil bulk density (Krishnakumar *et al*. 2013) whilst increasing WHC. Zhang *et al*. (2011) showed that biochar amendment led to a decrease in BD and the higher the application rate the lower the bulk density. Alberquerque *et al*. (2014) found a decrease in bulk density after biochar amendment and the decrease differed according to the type of biochar used. A decrease in the soil BD leads to increased soil aeration (Major 2010) and porosity thereby enhancing plant root growth (Basso *et al.* 2012). Nelissen *et al*. (2014) reported a reduction in soil bulk density from 1.47 mg/m^3 to 1.44 mg/cm^3 thus suggesting that biochar can be used in ameliorating soil compaction.

5.6 Conclusion

Biochar amendment led to improved soil organic C, Ca, Mg, K, P, Na, N and soil P with high concentrations in the 0-10 cm depth at high application rates. Soil pH was significantly increased in the 0-10 cm depth after biochar application. Soil bulk density was significantly reduced while soil water holding capacity was significantly improved especially in the 0-10 cm depth at high biochar application rates.

The biochar amendment resulted in high yields of *B. napus* and the higher the application rate the higher the yield which could be due to a direct supply of nutrients by biochar as well as reduced soil bulk density and improved soil water retention. Leaf length, leaf area and moisture content of *B. napus* significantly improved after biochar amendment. Therefore, biochar application at 20 t/ha may be an option for improving soil fertility, yield of *B. napus* and reduce soil bulk density by communal farmers.

CHAPTER 6

6.0 General Discussion

Poor soil fertility has impacted Sub-Saharan Africa negatively resulting in reduced agricultural productivity (Diagana 2003) and Zimbabwe is not spared. The majority of Zimbabwean population live in marginal areas that are not suitable for crop production due to low rainfall and poor soil fertility. Farmers have explored the option of cultivating fertile seasonal wetlands as a buffer against climate change, but lately soil fertility in these seasonal wetlands is decreasing and most of them are drying out. Therefore, there is need to enhance agriculture, which is key to addressing food shortages (Asenso-Okyere and Jemaneh 2012). Since inorganic fertilisers are expensive for most communal farmers, there is need to explore other sustainable climate smart sources of nutrients which are cheap and locally available like biochar that can improve agricultural productivity. Biochar is produced using locally available raw materials, lasts longer in the soil and can improve soil physical and chemical properties thereby improving plant productivity.

Currently, besides inorganic fertilisers, communal farmers use livestock manure, termite mounts and compost for agricultural production. However, these last only for a few years in the soil and is not enough to meet the demand for all smallholder farmers. Therefore, a long term remedy is needed which is cheaper to produce and can be available to all smallholder farmers.

Biochar amendment resulted in a significant increase ($p<0.05$) in the growth of *B. napus* regardless of season. The improvement in the growth performance of *B. napus* can be attributed to reduced bulk density and liming effect on the soil. Reduction in soil bulk density could explain the improved yield since it leads to improved soil aggregation as well as soil aeration (Major 2010; Krishnakumar *et al*. 2013) and porosity thereby enhancing plant root growth (Basso *et al.* 2012) thus improved plant growth.

Increased soil pH could have resulted to increased solubility and availability of the nutrients which were added by biochar application and those that were already in the soil. The optimum pH for *B. napus* is 5.5 – 7 (Musara and Chitamba 2015) and after biochar amendment, the pH was raised to closer to 7. The raised pH may also have caused a reduction in Al toxicity in the soil and therefore caused an increase in crop productivity.

Akom *et al*. (2016) reported no significant effects in biomass production after addition of wood shaving biochar to the soil. This could be as a result of nutrient fixing on the surface of the biochar. Therefore biochar may need to be applied together with inorganic fertilisers such as ammonium nitrate to improve crop productivity. Yao *et al.* (2015) found a significant increase in the yield of green pepper after biochar was blended with inorganic fertilisers. Mete *et al*. (2015) also found a further increase in soya bean yield after biochar was applied together with inorganic fertilisers.

As biochar application rate was increased, *B. napus* yield and water holding capacity also increased while soil bulk density decreased. A decrease in the soil BD can also explain an improvement in the crop yields in both seasons. Low bulk density improves the soil aeration and porosity of the soil thereby enhancing root growth (Basso *et al*. 2012) thereby improving crop productivity. Other studies also reported a reduction in crop diseases after biochar amendment (Matsubara *et al*. 2002; Elad *et al*. 2010; Elmer and Pignatello 2011), which may also have led to an increase in yield of *B. napus*. Usman *et al.* (2016) found that biochar applied under arid climatic conditions resulted in improved crop performance as well as the quality of crops.

Ca, Mg, K and P were significantly increased after biochar application due to mineralisation (Fischer and Glaser 2012). Ash content in biochar may release exchangeable bases in the soil thereby increasing soil available Ca, Na and K content. An increase in available K after biochar amendment was also reported in other studies (McElligot 2011; Schulz and Glaser 2012; Brewer *et al.* 2012; Kelly *et al*. 2015) due to ash content in the biochar. Biochar type and application rates have an effect on soil K with the highest amount of K in the soya bean stover biochar treatments applied at 20 t/ha. This could be due to the high amount of K in soya bean stover biochar (4%) (Table 5.1). Increasing soil pH neutralises the Fe and Al in the soil thus making P available for plant uptake (Cui *et al*. 2011). High soil P content in the 0-10 cm depth was due to adsorption of P on biochar surfaces, thus reducing P leaching (Beck *et al*. 2011). High SOC was due to the high amount of C in the biochar (Liang *et al*. 2006; Solomon *et al*. 2007) and the high the application rate, the high the amount of SOC (Zhang *et al*. 2013).

6.1 Conclusion

It is concluded that biochar application significantly reduced soil bulk density and increased soil organic C, Ca, Mg, K, Na, N, P and soil pH with high concentrations in the 0-10 cm depth except for mineral N which was lowest in the 0-10 cm depth. WHC was significantly improved after biochar amendment while bulk density was reduced, and the higher the application rate, the lower the bulk density. Biochar amendment also significantly increased the growth performance of *B. napus* with the application rate of 20 Mg/ha giving the highest yield of *B. napus*. Therefore, biochar from plant material applied at 20 Mg/ha can be used as a liming material and soil conditioner to improve plant productivity in Zimbabwe. However, long term studies under biochar amendment with diverse crops in different soil types are therefore recommended.

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APPENDICES

Appendix 1

WALKLEY-BLACK METHOD

Equipment:

1. 500-mL Erlenmeyer flasks.
2. 10-mL pipette.
3. 10-and 20-mL dispensers.
4. 50-mL burette.
5. Analytical balance.
6. Magnetic stirrer.
7. Incandescent lamp.

Reagents:

1. H_3PO_4, 85%.
2. H_2SO_4, concentrated (96%).
3. NaF, solid.
4. Standard 0. 167*M* $K_2Cr_2O_7$: Dissolve 49.04 g of dried (105^{o}C) $K_2Cr_2O_7$ in water and dilute to 1 L.
5. 0.5 *M* Fe^{2+} solution: Dissolve 196.1 g of $Fe(NH_4)_2(SO_4)•6H_2O$ in 800 mL of water containing 20 mL of concentrated H_2SO_4 and dilute to 1 L. The Fe^{2+} in this solution oxidizes slowly on exposure to air so it must be standardized against the dichromate daily.
6. Ferroin indicator: Slowly dissolve 3.71 g of o-phenanthroline and 1.74 g of $FeSO_4•7H_2O$ in 250 mL of water.

Procedure:

1. Weigh out 0.10 to 2.00 g dried soil (ground to <60 mesh) and transfer to a 500-mL Erlenmeyer flask. The sample should contain 10 to 25 mg of organic C (17 to 43 mg organic matter). For a 1 g soil sample, this would be 1.2 to 4.3% organic matter. Use up to 2.0 g of sample for light coloured soils and 0.1 g for organic soils.

2. Add 10 mL of 0.167 *M* $K_2Cr_2O_7$ by means of a pipette.

3. Add 20 mL of concentrated H_2SO_4 by means of dispenser and swirl gently to mix. Avoid excessive swirling that would result in organic particles adhering to the sides of the flask out of the solution.

4. Allow to stand 30 minutes. The flasks should be placed on an insulation pad during this time to avoid rapid heat loss.

5 Dilute the suspension with about 200 mL of water to provide a clearer suspension for viewing the endpoint.

6. Add 10 mL of 85% H_3PO_4, using a suitable dispenser, and 0.2 g of NaF. The H_3PO_4 and NaF are added to complex Fe^{3+} which would interfere with the titration endpoint.

7. Add 10 drops of ferroin indicator. The indicator should be added just prior to titration to avoid deactivation by adsorption onto clay surfaces.

8. Titrate with 0.5 *M* Fe^{2+} to a burgundy endpoint. The colour of the solution at the beginning is yellow-orange to dark green, depending on the amount of unreacted $Cr_2O_7^{2-}$ remaining, which shifts to a turbid gray before the endpoint and then changes sharply to a wine red at the endpoint. Use of a magnetic stirrer with an incandescent light makes the endpoint easier to see in the turbid system (fluorescent lighting gives a different endpoint colour). Alternatively use a Pt electrode to determine the endpoint after step 5 above. This will eliminate uncertainty in determining the endpoint by colour change. If less than 5 mL of Fe^{2+} solution was required to back titrate the excess $Cr_2O_7^{2-}$ there was insufficient $Cr_2O_7^{2-}$ present, and the analysis should be repeated either by using a smaller sample size or doubling the amount of $K_2Cr_2O_7$ and H_2SO_4.

9. Run a reagent blank using the above procedure without soil. The blank is used to standardize the Fe^{2+} solution daily.

10. Calculate %C and % organic matter:
a. *% Easily Oxidizable Organic C*

%C = ((B-S) x M of Fe^{2+} x 12 x 100)/ g of soil x 4000

where:
B = mL of Fe^{2+} solution used to titrate blank
S = mL of Fe^{2+} solution used to titrate sample
12/4000 = milliequivalent weight of C in g.

To convert easily oxidizable organic C to total C, divide by 0.77 (or multiply by 1.30) or other experimentally determined correction factor. To convert total organic C to organic matter use the following equation:

b. % *Organic Matter = (*% total C x 1.72)/0.58

Appendix 2

Mehlich 3-Extractable Elements

7.2 MATERIALS AND REAGENTS
1 Reciprocating shaker
2 Erlenmeyer flasks 125 mL
3 Filter funnels
4 Filter paper (Whatman #42)
5 Disposable plastic vials
6 Instrumentation common in soil chemistry laboratories such as: spectrophotometer for conventional colorimetry or automated colorimetry (e.g., Technicon AutoAnalyzer; Lachat Flow Injection System); flame photometer; or ICP-OES or ICP-MS
7 M3 extracting solution:
a. Stock solution M3: (1:5 M NH4F þ 0:1 M EDTA). Dissolve 55.56 g of ammonium fluoride (NH4F) in 600 mL of deionized water in a 1 L volumetric flask.
Add 29.23 g of EDTA to this mixture, dissolve, bring to 1 L volume using deionized water, mix thoroughly, and store in plastic bottle.
b. In a 10 L plastic carboy containing 8 L of deionized water, dissolve 200.1 g of ammonium nitrate (NH4NO3) and add 100 mL of stock solution M3, 115 mL concentrated acetic acid (CH3COOH), 82 mL of 10% v=v nitric acid (10 mL concentrated HNO3 in 100 mL of deionized water), bring to 10 L with deionized water and mix thoroughly.
c. The pH of the extracting solution should be 2.3+0.2.
8 Solutions for the manual determination of phosphorus:

a. Solution A: dissolve 12 g of ammonium molybdate ð(NH4)6Mo7O24 _ 4H2OÞ in 250 mL of deionized water. In a 100 mL flask, dissolve 0.2908 g of potassium antimony tartrate in 80 mL of deionized water. Transfer these two solutions into a 2 L volumetric flask containing 1000 mL of 2:5 M H2SO4 (141 mL concentrated H2SO4 diluted to 1 L with deionized water), bring to 2 L with deionized water, mix thoroughly, and store in the dark at 48C.
b. Solution B: dissolve 1.056 g of ascorbic acid in 200 mL of solution A. Solution B should be fresh and prepared daily.
c. Standard solution of P: use certified P standard or prepare a solution of 100 mg mL_1 P by dissolving 0.4393 g of KH2PO4 in 1 L of deionized water.
Prepare standard solutions of 0, 0.5, 1, 2, 5, and 10 mg mL_1 P in diluted M3 extractant.
9 Solutions for K, Ca, Mg, and Na determination by atomic absorption:
a. Lanthanum chloride (LaCl3) solution: 10% (w=v).
b. Concentrated solution of cesium chloride (CsCl) and LaCl3: dissolve 3.16 g of CsCl in 100 mL of the 10% LaCl3 solution.
c. Combined K and Na standard solutions: use certified atomic absorption standard and prepare solutions of 0.5, 1.0, 1.5, 2.0 and 0.3, 0.6, 0.9, 1:2 mg mL_1 of K and Na, respectively.
d. Combined Ca and Mg standard solutions. Prepare 2, 4, 6, 8, 10 and 0.2, 0.4, 0.6, 0.8, 1:0 mg mL_1 of Ca and Mg, respectively.
10 Standard solution for Cu, Zn, and Mn determination by atomic absorption:
a. Combined Cu and Zn standard solution: 0, 0.2, 0.4, 0.8, 1.2 to 2.0 mg mL_1 of Cu and of Zn in M3 extractant.
b. Mn standard solutions: prepare 0, 0.4, 0.8, 1.2 to 4 mg mL_1 of Mn in diluted M3 extractant.
7.3 PROCEDURE
7.3.1 EXTRACTION
1 Weigh 3 g of dry soil passed through a 2 mm sieve into a 125 mL Erlenmeyer flask.
2 Add 30 mL of the M3 extracting solution (soil:solution ratio 1:10).
3 Shake immediately on reciprocating shaker for 5 min (120 oscillations min_1).
4 Filter through M3-rinsed Whatman #42 filter paper into plastic vials and store at 48C until analysis.
5 Analyze elements in the filtrate as soon as possible using either an automated or manual method as described below.
7.3.2 DETERMINATION OF P BY MANUAL COLORIMETRIC METHOD
1 Pipet 2 mL of the clear filtrate or standard (0 to 10 mg mL_1) P solution into a 25 mL volumetric flask. The sample aliquot cannot contain more than 10 mg of P and dilution of the filtrate with M3 maybe required.
2 Add 15 mL of distilled water and 4 mL of solution B, make to volume with distilled water and mix.
3 Allow 10 min for color development, and measure the absorbance at 845 nm.
7.3.3 DETERMINATION OF K, Ca, Mg, AND Na BY ATOMIC ABSORPTION OR BY FLAME EMISSION
Precipitation problems can result from the mixture of the CsCl---LaCl2 solution with the M3 extract. It is therefore recommended that the extracts be diluted (at least 1:10 final dilution) as indicated below to avoid this problem.
1Pipet 1 to 5 mL of filtrate into a 50 mL volumetric flask.
2 Add approximately 40 mL of deionized water and mix.
3 Add 1 mL of the CsCl---LaCl3 solution, bring to volume with deionized water and mix.
4 Determine Ca Mg by atomic absorption and K, Na by flame emission.
7.3.4 DETERMINATION OF Cu, Zn, AND Mn BY ATOMIC ABSORPTION
The Cu and Zn concentrations in the extract are determined without dilution while the Mn concentration is determined in diluted M3 extract.

Appendix 3
MEASUREMENT OF SOIL pH

EQUIPMENT

pH meter equipped with glass and calomel electrodes
50 mL plastic beakers
Stirring rods

REAGENTS
Calcium chloride solution ($CaCl_2$) 0.01M
Standard buffer solutions: pH 4.0, 7.0

PROCEDURE
1. Measure out 15 g of mineral soil into a 50mL beaker with a graduated scoop. Add 30 mL of 0.01M $CaCl_2$ and stir into suspension. Stir again after 15-20 minutes and allow to stand for 30 minutes to allow sediment to settle.
NOTE: For organic samples a 1:4 soil-solution ratio is used, as organic soil tends to absorb more solution.
2. Standardize the pH meter as follows:
i) set the pH meter at pH 7.0 with standard buffer solution of pH 7.0 and set the temperature compensator at the temperature of the buffer.
ii) check the meter with a pH 4.0 buffer solution and adjust if necessary.

3. Immerse the glass and calomel electrodes into the partly settled suspension (do not immerse electrodes to the bottom of the container) and record pH when reading has been stabilized.

Appendix 4

Effects of biochar amendment on C, Ca, K, Mg, N, Na, P, pH, bulk density and water holding capacity in the wet season

Analysis of variance
Variate: C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	1.8881	0.4720	1.31	0.288
Depth	2	3.9833	1.9917	5.53	0.009
Type.Depth	8	0.3775	0.0472	0.13	0.997
Residual	30	10.7953	0.3598		
Total	44	17.0442			

Analysis of variance
Variate: Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.052962	0.013240	2.12	0.103
Depth	2	0.391430	0.195715	31.35	<.001
Type.Depth	8	0.011691	0.001461	0.23	0.981
Residual	30	0.187278	0.006243		
Total	44	0.643360			

Analysis of variance
Variate: K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.00068041	0.00017010	1.87	0.142
Depth	2	0.00089215	0.00044607	4.90	0.014
Type.Depth	8	0.00113176	0.00014147	1.55	0.181

Residual	30	0.00273348	0.00009112		
Total	44	0.00543780			

Analysis of variance
Variate: Mg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.029270	0.007317	3.19	0.027
Depth	2	0.155294	0.077647	33.88	<.001
Type.Depth	8	0.022494	0.002812	1.23	0.318
Residual	30	0.068763	0.002292		
Total	44	0.275820			

Analysis of variance: N

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Type ignoring Depth	4	61.55	15.39	0.59	0.675
Type eliminating Depth	4	78.18	19.54	0.75	0.573
Depth ignoring Type	2	416.55	208.28	7.99	0.004
Depth eliminating Type	2	433.19	216.59	8.30	0.003
Type.Depth	8	69.29	8.66	0.33	0.941
Residual	16	417.33	26.08		
Total	30	981.35	32.71		

Analysis of variance
Variate: Na

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.00262957	0.00065739	7.07	<.001
Depth	2	0.05732654	0.02866327	308.24	<.001
Type.Depth	8	0.00210493	0.00026312	2.83	0.018
Residual	30	0.00278972	0.00009299		
Total	44	0.06485077			

Analysis of variance
Variate: P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	65.003	16.251	2.55	0.060
Depth	2	490.784	245.392	38.49	<.001
Type.Depth	8	17.327	2.166	0.34	0.943
Residual	30	191.240	6.375		
Total	44	764.354			

Analysis of variance
Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	13.8634	3.4658	19.52	<.001
Depth	2	5.5568	2.7784	15.65	<.001
Type.Depth	8	2.1998	0.2750	1.55	0.182
Residual	30	5.3254	0.1775		
Total	44	26.9454			

Analysis of variance
Variate: Bulk density

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.1324363	0.0331091	124.96	<.001
Depth	2	0.3340438	0.1670219	630.37	<.001

Type.Depth	8	0.0022789	0.0002849	1.08	0.406
Residual	30	0.0079488	0.0002650		
Total	44	0.4767078			

Analysis of variance
Variate: Water holding capacity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	300.72	75.18	1.21	0.328
Depth	2	736.11	368.06	5.91	0.007
Type.Depth	8	653.45	81.68	1.31	0.276
Residual	30	1868.18	62.27		
Total	44	3558.46			

Appendix 5

Effects of biochar amendment on C, Ca, K, Mg, N, Na, P, pH, bulk density and water holding capacity in the dry season

Analysis of variance
Variate: C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	2.0027	0.5007	1.37	0.266
Depth	2	24.3295	12.1647	33.40	<.001
Type.Depth	8	1.1863	0.1483	0.41	0.907
Residual	30	10.9256	0.3642		
Total	44	38.4441			

Analysis of variance
Variate: Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.04839	0.01210	0.79	0.541
Depth	2	3.33479	1.66739	108.79	<.001
Type.Depth	8	0.03624	0.00453	0.30	0.962
Residual	30	0.45981	0.01533		
Total	44	3.87923			

Analysis of variance
Variate: K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.0023290	0.0005823	4.35	0.007
Depth	2	0.0027379	0.0013689	10.23	<.001
Type.Depth	8	0.0010787	0.0001348	1.01	0.451
Residual	30	0.0040155	0.0001338		
Total	44	0.0101611			

Analysis of variance
Variate: Mg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.020204	0.005051	3.32	0.023
Depth	2	1.769684	0.884842	581.49	<.001
Type.Depth	8	0.005445	0.000681	0.45	0.883
Residual	30	0.045651	0.001522		
Total	44	1.840983			

Analysis of variance: N

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Type ignoring Depth	4	25.527	6.382	0.70	0.606
Type eliminating Depth	4	26.508	6.627	0.72	0.589

Depth ignoring Type	2	229.855	114.928	12.54	< 0.001
Depth eliminating Type	2	230.836	115.418	12.59	< 0.001
Type.Depth	8	45.164	5.646	0.62	0.753
Residual	16	146.667	9.167		
Total	30	448.194	14.940		

Analysis of variance
Variate: Na

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.0010803	0.0002701	2.06	0.112
Depth	2	0.0461210	0.0230605	175.51	<.001
Type.Depth	8	0.0001844	0.0000230	0.18	0.993
Residual	30	0.0039418	0.0001314		
Total	44	0.0513274			

Analysis of variance
Variate: P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	121.581	30.395	4.35	0.007
Depth	2	1020.300	510.150	72.98	<.001
Type.Depth	8	91.156	11.395	1.63	0.158
Residual	30	209.703	6.990		
Total	44	1442.741			

Analysis of variance
Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	30.5761	7.6440	37.81	<.001
Depth	2	1.1994	0.5997	2.97	0.067
Type.Depth	8	0.4694	0.0587	0.29	0.964
Residual	30	6.0645	0.2022		
Total	44	38.3095			

Analysis of variance
Variate: BD

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	0.057920	0.014480	8.09	<.001
Depth	2	0.629636	0.314818	175.94	<.001
Type.Depth	8	0.083022	0.010378	5.80	<.001
Residual	30	0.053681	0.001789		
Total	44	0.824260			

Analysis of variance
Variate: WHC

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	4	158.96	39.74	1.63	0.193
Depth	2	694.11	347.06	14.22	<.001
Type.Depth	8	334.35	41.79	1.71	0.136
Residual	30	732.22	24.41		
Total	44	1919.65			

Appendix 6

The effect of type and application rate of biochar on C, Ca, K, Mg, N, Na, P, pH, bulk density, water holding capacity and *B. napus* yield in the wet season.

Analysis of variance

Variate: C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	0.4568	0.2284	1.49	0.233
Type	2	0.0235	0.0117	0.08	0.926
Rate	3	0.5785	0.1928	1.26	0.296
depth	2	15.5792	7.7896	50.75	<.001
Type.Rate	6	0.5910	0.0985	0.64	0.696
Type.depth	4	0.4014	0.1004	0.65	0.626
Rate.depth	6	0.2338	0.0390	0.25	0.956
Type.Rate.depth	12	0.6223	0.0519	0.34	0.979
Residual	70	10.7439	0.1535		
Total	107	29.2303			

Analysis of variance
Variate: Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	2.1502	1.0751	2.08	0.133
Type	2	0.3459	0.1729	0.33	0.717
Rate	3	5.3584	1.7861	3.45	0.021
depth	2	12.6954	6.3477	12.28	<.001
Type.Rate	6	2.6440	0.4407	0.85	0.534
Type.depth	4	0.6615	0.1654	0.32	0.864
Rate.depth	6	2.1324	0.3554	0.69	0.660
Type.Rate.depth	12	1.3418	0.1118	0.22	0.997
Residual	70	36.1977	0.5171		
Total	107	63.5273			

Analysis of variance
Variate: Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	2.1502	1.0751	2.08	0.133
Type	2	0.3459	0.1729	0.33	0.717
Rate	3	5.3584	1.7861	3.45	0.021
depth	2	12.6954	6.3477	12.28	<.001
Type.Rate	6	2.6440	0.4407	0.85	0.534
Type.depth	4	0.6615	0.1654	0.32	0.864
Rate.depth	6	2.1324	0.3554	0.69	0.660
Type.Rate.depth	12	1.3418	0.1118	0.22	0.997
Residual	70	36.1977	0.5171		
Total	107	63.5273			

Analysis of variance
Variate: K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	0.0002488	0.0001244	0.63	0.536
Type	2	0.0058458	0.0029229	14.78	<.001
Rate	3	0.0059887	0.0019962	10.09	<.001
depth	2	0.0298903	0.0149452	75.57	<.001
Type.Rate	6	0.0033651	0.0005609	2.84	0.016
Type.depth	4	0.0067268	0.0016817	8.50	<.001
Rate.depth	6	0.0024864	0.0004144	2.10	0.065
Type.Rate.depth	12	0.0039829	0.0003319	1.68	0.091
Residual	70	0.0138442	0.0001978		
Total	107	0.0723790			

Analysis of variance
Variate: Mg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Block	2	0.00658	0.00329	0.22	0.802
Type	2	0.01519	0.00759	0.51	0.603
Rate	3	0.14416	0.04805	3.23	0.028
depth	2	1.45610	0.72805	48.90	<.001
Type.Rate	6	0.06267	0.01045	0.70	0.649
Type.depth	4	0.06070	0.01517	1.02	0.403
Rate.depth	6	0.11635	0.01939	1.30	0.268
Type.Rate.depth	12	0.09195	0.00766	0.51	0.898
Residual	70	1.04213	0.01489		
Total	107	2.99582			

Analysis of variance
Variate: N

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block	2		2308.08	1154.04	24.11	<.001
Type	2		141.79	70.89	1.48	0.238
Rate	3		617.55	205.85	4.30	0.009
depth	2		1024.50	512.25	10.70	<.001
Type.Rate	6		360.28	60.05	1.25	0.297
Type.depth	4		134.74	33.69	0.70	0.593
Rate.depth	6		116.60	19.43	0.41	0.871
Type.Rate.depth	12		506.92	42.24	0.88	0.570
Residual	46	(24)	2202.15	47.87		
Total	83	(24)	5322.70			

Analysis of variance
Variate: Na

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	2.162E-05	1.081E-05	1.70	0.190
Type	2	1.140E-06	5.698E-07	0.09	0.914
Rate	3	2.110E-05	7.033E-06	1.11	0.352
depth	2	6.156E-03	3.078E-03	484.84	<.001
Type.Rate	6	3.831E-05	6.385E-06	1.01	0.429
Type.depth	4	1.183E-05	2.957E-06	0.47	0.761
Rate.depth	6	2.326E-05	3.877E-06	0.61	0.721
Type.Rate.depth	12	8.316E-05	6.930E-06	1.09	0.381
Residual	70	4.444E-04	6.348E-06		
Total	107	6.800E-03			

Analysis of variance
Variate: P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	157.515	78.758	16.28	<.001
Type	2	21.907	10.953	2.26	0.112
Rate	3	93.934	31.311	6.47	<.001
depth	2	1470.738	735.369	151.97	<.001
Type.Rate	6	89.295	14.883	3.08	0.010
Type.depth	4	23.629	5.907	1.22	0.310
Rate.depth	6	10.233	1.706	0.35	0.906
Type.Rate.depth	12	28.465	2.372	0.49	0.914
Residual	70	338.733	4.839		
Total	107	2234.449			

Analysis of variance
Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	0.6240	0.3120	1.15	0.322
Type	2	0.3662	0.1831	0.68	0.512
Rate	3	1.7874	0.5958	2.20	0.096

depth	2	2.2225	1.1113	4.10	0.021
Type.Rate	6	0.9210	0.1535	0.57	0.756
Type.depth	4	0.2254	0.0563	0.21	0.933
Rate.depth	6	0.4619	0.0770	0.28	0.943
Type.Rate.depth	12	0.9809	0.0817	0.30	0.987
Residual	70	18.9711	0.2710		
Total	107	26.5605			

Variate: BD

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.003782	0.001891	1.47	0.238
Rate	3	0.117225	0.039075	30.29	<.001
Depth	2	0.990689	0.495345	383.96	<.001
Type.Rate	6	0.005849	0.000975	0.76	0.607
Type.Depth	4	0.000750	0.000187	0.15	0.965
Rate.Depth	6	0.013625	0.002271	1.76	0.120
Type.Rate.Depth	12	0.022757	0.001896	1.47	0.156
Residual	72	0.092886	0.001290		
Total	107	1.247564			

Variate: WHC

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	55.56	27.78	0.34	0.713
Rate	3	110.66	36.89	0.45	0.718
Depth	2	9136.42	4568.21	55.80	<.001
Type.Rate	6	425.40	70.90	0.87	0.524
Type.Depth	4	16.32	4.08	0.05	0.995
Rate.Depth	6	418.79	69.80	0.85	0.534
Type.Rate.Depth	12	630.85	52.57	0.64	0.799
Residual	72	5894.14	81.86		
Total	107	16688.14			

Variate: Yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	2.886	1.443	0.16	0.849
Rate	3	200.868	66.956	7.58	<.001
Type.Rate	6	4.779	0.797	0.09	0.997
Residual	240	2120.643	8.836		
Total	251	2329.176			

Appendix 7

The effect of type and application rate of biochar on C, Ca, K, Mg, N, Na, P, pH, bulk density, water holding capacity and *B. napus* yield in the dry season.

Analysis of variance

Variate: C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.3787	0.1894	0.81	0.451
Rate	3	2.9636	0.9879	4.20	0.008
Depth	2	57.1732	28.5866	121.66	<.001
Type.Rate	6	2.0391	0.3399	1.45	0.209
Type.Depth	4	0.7025	0.1756	0.75	0.563
Rate.Depth	6	3.8225	0.6371	2.71	0.020
Type.Rate.Depth	12	1.3995	0.1166	0.50	0.910
Residual	72	16.9183	0.2350		
Total	107	85.3974			

Analysis of variance
Variate: Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.198	0.099	0.08	0.919
Rate	3	8.438	2.813	2.40	0.075
Depth	2	71.259	35.630	30.44	<.001
Type.Rate	6	3.498	0.583	0.50	0.808
Type.Depth	4	0.801	0.200	0.17	0.952
Rate.Depth	6	4.295	0.716	0.61	0.720
Type.Rate.Depth	12	1.378	0.115	0.10	1.000
Residual	72	84.266	1.170		
Total	107	174.133			

Analysis of variance
Variate: K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.0061797	0.0030898	9.90	<.001
Rate	3	0.0127797	0.0042599	13.66	<.001
Depth	2	0.0208910	0.0104455	33.48	<.001
Type.Rate	6	0.0030976	0.0005163	1.65	0.145
Type.Depth	4	0.0030123	0.0007531	2.41	0.057
Rate.Depth	6	0.0079848	0.0013308	4.27	<.001
Type.Rate.Depth	12	0.0042816	0.0003568	1.14	0.340
Residual	72	0.0224610	0.0003120		
Total	107	0.0806876			

Analysis of variance
Variate: Mg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.00691	0.00345	0.07	0.934
Rate	3	0.55455	0.18485	3.65	0.016
Depth	2	8.04485	4.02242	79.50	<.001
Type.Rate	6	0.17074	0.02846	0.56	0.759
Type.Depth	4	0.00574	0.00143	0.03	0.998
Rate.Depth	6	0.25000	0.04167	0.82	0.555
Type.Rate.Depth	12	0.07363	0.00614	0.12	1.000
Residual	72	3.64274	0.05059		
Total	107	12.74916			

Analysis of variance
Variate: N

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Type	2		143.11	71.56	0.77	0.467
Rate	3		597.95	199.32	2.15	0.106
Depth	2		89.22	44.61	0.48	0.620
Type.Rate	6		592.79	98.80	1.07	0.395
Type.Depth	4		6.82	1.70	0.02	0.999
Rate.Depth	6		107.17	17.86	0.19	0.977
Type.Rate.Depth	12		759.73	63.31	0.68	0.758
Residual	48	(24)	4440.67	92.51		
Total	83	(24)	5923.81			

Analysis of variance
Variate: Na

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.0000804	0.0000402	0.20	0.820
Rate	3	0.0003185	0.0001062	0.53	0.665
Depth	2	0.2036704	0.1018352	505.73	<.001
Type.Rate	6	0.0005769	0.0000961	0.48	0.823

Type.Depth	4	0.0008685	0.0002171	1.08	0.374
Rate.Depth	6	0.0025501	0.0004250	2.11	0.062
Type.Rate.Depth	12	0.0016186	0.0001349	0.67	0.774
Residual	72	0.0144981	0.0002014		
Total	107	0.2241814			

Analysis of variance
Variate: P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	21.80	10.90	0.51	0.606
Rate	3	119.77	39.92	1.85	0.146
Depth	2	1699.90	849.95	39.38	<.001
Type.Rate	6	142.16	23.69	1.10	0.372
Type.Depth	4	12.92	3.23	0.15	0.963
Rate.Depth	6	105.35	17.56	0.81	0.563
Type.Rate.Depth	12	152.33	12.69	0.59	0.845
Residual	72	1553.81	21.58		
Total	107	3808.04			

Analysis of variance
Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	1.2868	0.6434	1.76	0.180
Rate	3	4.2026	1.4009	3.83	0.013
Depth	2	9.7252	4.8626	13.28	<.001
Type.Rate	6	3.0524	0.5087	1.39	0.231
Type.Depth	4	0.3910	0.0977	0.27	0.898
Rate.Depth	6	0.7276	0.1213	0.33	0.918
Type.Rate.Depth	12	0.7678	0.0640	0.17	0.999
Residual	72	26.3645	0.3662		
Total	107	46.5180			

Variate: BD

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.05993	0.02996	2.84	0.065
Rate	3	0.13237	0.04412	4.18	0.009
Depth	2	2.69611	1.34806	127.74	<.001
Type.Rate	6	0.09522	0.01587	1.50	0.189
Type.Depth	4	0.01094	0.00273	0.26	0.903
Rate.Depth	6	0.11960	0.01993	1.89	0.094
Type.Rate.Depth	12	0.17132	0.01428	1.35	0.209
Residual	72	0.75982	0.01055		
Total	107	4.04531			

Variate: WHC

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	1.40	0.70	0.02	0.983
Rate	3	471.26	157.09	3.88	0.012
Depth	2	8226.61	4113.31	101.71	<.001
Type.Rate	6	78.73	13.12	0.32	0.922
Type.Depth	4	30.30	7.57	0.19	0.944
Rate.Depth	6	503.80	83.97	2.08	0.067
Type.Rate.Depth	12	531.67	44.31	1.10	0.377
Residual	72	2911.83	40.44		
Total	107	12755.61			

Variate: Yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Type	2	0.691	0.345	0.27	0.764

Rate	3	106.143	35.381	27.69	<.001
Type.Rate	6	2.774	0.462	0.36	0.902
Residual	168	214.674	1.278		
Total	179	324.281			