GROWTH VARIABLES, YIELD AND NITROGEN FIXATION OF BAMBARA GROUNDNUT (*Vigna subterranea* L. Verdc.) LANDRACES AT DIFFERENT RATES OF CHRISTMAS ISLAND ROCK PHOSPHATE AND RICE BIOCHAR ON TROPICAL ACID SOILS.

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Abstract

Bambara groundnut presents a great adaptation potential for mitigating climate change and as a potential alternative crop for the future in its production regions and beyond. Experiments were conducted at the Field Research Centre of the Crops for the Future and the Screenhouse of the University of Nottingham Malaysia Campus to determine the growth variables, yield and nitrogen fixation of Bambara groundnut landraces at different rates of Christmas Island Rock Phosphate and rice biochar in the study area. The treatments consisted of three Bambara groundnut landraces [Ex-Sokoto, Kaaro and NN-1, for which two (Ex-Sokoto and Kaaro) were maintained after the first experiment], two biochar levels (0 and 10 t ha^{-1}) and four levels of rock phosphate (0, 20, 40 and 60 kg P_2O_5 ha^{-1}, the equivalent of 0, 555.6, 1111.1 and 1666.7 kg ha^{-1} Christmas Island Rock Phosphate). The treatments in experiment 1 and 3 were laid out in a randomized complete block design (RCBD) replicated three times, whereas experiment 2 was laid out in a completely randomized design (CRD) replicated three times. For all the experiments, data were collected on growth, yield and nitrogen fixation of the crop. The results obtained revealed grain yield and N fixed ranging from 703-2256 kg ha^{-1} and 32-81 kg ha^{-1}, respectively in experiment 1, 13.2-18.0 g $plant^{-1}$ and 587-894 mg $plant^{-1}$, respectively in experiment 2 and 891-1220 kg ha^{-1} and 101.6-103.4 kg ha^{-1}, respectively in experiment 3, which are comparable to the yields obtained in other regions. Hence, Bambara groundnut can adapt to the tropical acid soil and the growing conditions in the study area. The two field experiments confirm Ex-Sokoto landrace to perform better in the study area in terms of yield than Kaaro landrace. Growing Bambara groundnut and returning the residues (haulm + shells) back to the soil resulted in net addition of N to the soil in the range of 1 to 25.6 kg ha^{-1}, 150-261 mg $plant^{-1}$ and 63.3-74.1 kg ha^{-1} observed in experiment 1, 2 and 3, respectively. Application of biochar increased the yield and nitrogen fixation of the crop in the study area. However, the effect of rock phosphate

application on the yield and N fixation of the crop was only observed in the screenhouse studies and was optimum at the application rate of 40 kg P_2O_5 ha^{-1} (0.56 g kg^{-1} soil).

Thus, Ex-Sokoto landrace could be recommended for grain yield in the study area. Application of biochar at 10 t ha^{-1} alone was optimum for increased yield of the crop. The implication of the study is that farmers in the study area could apply 10 t ha^{-1} of biochar on Ex-Sokoto landrace to enhance the yield of the crop.

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Dedication

This research work is dedicated to my lovely parents

List of publications

1- Musa, M., Massawe, F., Mayes, S., Alshareef, I. and Singh, A. (2016) Nitrogen Fixation and N-Balance Studies on Bambara Groundnut (*Vigna subterranea* L. Verdc.) Landraces Grown on Tropical Acidic Soils of Malaysia. *Communications in Soil Science and Plant Analysis*, 47(4): 533-542.

Table of contents

List of figures

List of tables

CHARTER ONE

1. INTRODUCTION

1.1 General

1.1.1 Taxonomy and botany

Bambara groundnut (*Vigna subterranea* (L.) Verdc., syn *Voandzeia subterranea* (L.) Thours), a pulse legume, is an indigenous African legume (Collinson *et al*., 1996). The crop is herbaceous annual legume of the *Fabaceae* family with chromosome number of 2n = 22. The crop has a spreading or bunched growth habit and consists of branched, running stems with short internodes. The leaves which are trifoliate have erect petioles and alternate each other on the branch. Germination of the crop is hypogeal with the cotyledons remaining underground at emergence. The root system consists of a primary root which is the main axis and the secondary roots which appear at a certain depth below the ground level. Like other legumes the crop is capable of symbiotic relationship with nitrogen fixing bacteria belonging to the genus *Rhizobium* (Baudoin and Mergeai, 2001). After fertilization, the peduncle of the raceme elongates and forces the tip of the inflorescence under the ground by positive geotropism (downward growth). The fruits are formed below the ground in the same way as groundnut and hence, the name Bambara groundnut (Goli, 1997). The pods are indehiscent and are either smooth or slightly wrinkled containing one or two very hard subglobular seeds with variable seed coat colour (Baudoin and Mergeai, 2001).

1.1.2 Importance and utilization of the crop

The crop is an important local crop to Africa, often third in importance only to cowpea (*Vigna unguiculata* L. Walp.) and groundnut (*Arachis hypogaea* L.) among the major legumes that are grown in the region (Howell *et al*., 1994). It is also an important crop to Madagascar (Howell *et al*., 1994). The crop is grown mainly by subsistence farmers primarily for its seeds, which are consumed in various forms and dishes

(Brink *et al*., 2006; Ouedraogo *et al*., 2008). The crop is reported to be nutritionally superior to other legumes and a crop of choice to many Africans where it supplements cereal-based diets and plays an important role in meeting the protein requirement of resource poor farmers (Collinson *et al*., 2000; Azam-Ali *et al.,* 2001). The mature seeds are a rich source of protein (16-25%), carbohydrate (42-60%) and lipid (5-6%) (Brought and Azam-Ali, 1992), fibre (4.8%) and ash (3.4%) (Brink *et al.*, 2006). The protein composition of the crop contains 32.72% essential amino acids and 66.10% of non-essential amino acids (Rowland, 1993; Ouedraogo *et al*., 2008). The haulm is used as livestock feed in most of the drier parts of Africa. The fresh pods are boiled and eaten as snacks (Heller *et al*., 1997). The milk produced from the seed of the crop was found to be comparable in taste to that produced from cowpea, soybean and pigeon pea (Brough *et al*., 1993). Biological nitrogen (N) fixation, a distinctive characteristic of legumes and a natural process of significant importance to the world agriculture (Herridge *et al*., 2008; Unkovich *et al*., 2008) is among the major attributes of the crop and it is reported to fix 20-100 kg N ha^{-1} (Linnemann, 1991). Grain legumes such as Bambara groundnut are integral part of the traditional cropping systems which are grown as intercrops or in rotation with other crops (Dakora and Keya, 1997). Ncube *et al*. (2007) working on the residual benefit of some grain legumes to sorghum in rotation reported increase in the yield of the crop due to residual N.

1.1.3 Production and distribution

The centre of origin of the crop was thought to be Bambara, near Timbuktu in Central Mali, West Africa and hence the name Bambara groundnut (Karunaratne *et al*., 2011). However, recent evidences suggest that Bambara groundnut originated from North-eastern Nigeria and Northern Cameroun as confirmed by the presence of higher genetic diversity compared to other regions (Olukolu *et al*., 2012). In addition to its origin in sub-Saharan Africa, it is now found in South America, Asia and Oceania (Baudoin and Mergeai, 2001). The crop requires annual rainfall of between 600-700 mm, a day temperature between 20-28°C and a well-drained soil with a pH of 5.0 to 6.5 and can be grown in areas up to 1600 m above sea level with the climatic requirements in most cases similar to that of groundnut and cowpea (Swanevelder, 1998). The crop is second to cowpea as the most widely grown native African legume in south of the Sahara (Howell *et al*., 1994). The crop could be grown on hot and dry-regions which are marginal to other pulse crops and hence, a crop of choice for resource-poor farmers under low input farming system (Toungos *et al*., 2009; Yakubu *et al*., 2010). Compared to other legumes, the crop tolerates hot, dry and other harsh climatic conditions which makes it a farmer's crop of choice where other legumes such as cowpea and peanut fail to perform satisfactorily (Brink, 1997; Karunaratne *et al*., 2011).

The crop is also reported to be less susceptible to pest and diseases and to date there is no reported major pest and disease of the crop (Brink, 1997). The crop is able to grow and fix N under severe drought conditions where no other crops can survive (Dakora and Keya, 1997). As a food crop, it is grown throughout sub-Saharan Africa, stretching from the Sahel region of West Africa, across Central Africa to East Africa and then to Southern Africa (Jorgensen *et al*., 2010; Mohale *et al*., 2014). The crop also spreads in to new production areas such as Indonesia and Thailand in the Asian continent (Azam-Ali *et al*., 2001; Mohale *et al*., 2014). It is also cultivated to a lesser extent in tropical parts of the Americas and Australia (Brink *et al*., 2006). The crop is also reported to thrive in different agro-ecologies with soils of various pH, nutrients status, moisture, temperature and N fixing organisms in its production areas and beyond. Bambara groundnut like other legumes is susceptible to water logging due to the sensitivity of the rhizobia within the root nodules to anaerobic conditions

(Collinson *et al*., 1996). Compared to other legumes, nodule functioning in Bambara groundnut was observed to be tolerant of NO_3 ions in the rhizosphere which allows the use of inorganic N fertilizer for cereals grown as intercrops without inhibiting N fixation in the crop (Dakora, 1998). The yield of the crop varies from 50 to up to 4000 kg ha^{-1} (Swanevelder, 1998).

1.2 Problem statement and justification of the studies

With increasing demand for food due to increasing human population and decreasing land area available for cultivation as a result of continuous land development for non-agricultural purposes, there is the need to explore the alternative crops and production technologies that have contributed to food security in other parts of the world. Bambara groundnut identified as a complete balanced diet and a good supplement to cereal-based diets (Karikari *et al*., 1997) is an important potential alternative food crop that could be harnessed for increased food security in its production regions and beyond.

The ability of the crop to thrive in different agro-ecologies is remarkable and suggests its wider adaptability which if harnessed could be a potential alternative food legume in its current production regions and beyond (Azam-Ali *et al*., 2001; Mohale *et al*., 2014). Information on the field performance of Bambara groundnut in this region is limited. There is the need therefore to study the performance of various landraces with the aim of exploring the potentials of the crop on tropical acidic soils and identify a promising landrace for the study area. Reddy *et al*. (1993) reported that yield of groundnut crop could be increased up to 30-89% provided that high yielding varieties are identified. Bambara groundnut like other legumes has a high P requirement and as such is reported to be the most limiting nutrient for growth and yield of the crop (Lopez-Bucio *et al*., 2002). The production of the crop could be constrained by the inherent low soil P content of most of the production regions and a high cost of water soluble P fertilizers which are beyond the reach of tropical poor farmers (Fardeau and Zapata, 2002; FAO, 2004).

Evaluation of the crop's response to locally and easily available P sources such as rock phosphate could provide information on how to address the constraint and increase the yield of the crop. Herridge *et al*. (2008) reported high demand for accurate determination of global inputs of biologically fixed nitrogen in different agro-climates. Nutrients availability and uptake under sub humid tropical conditions could be impaired by increasing soil acidity with its associated problems (Bambara and Ndakidemi, 2009).

To date there is limited information on the influence of biochar application on the agronomic performance of legumes and in particular biological nitrogen fixation in Bambara groundnut, but research on corn reported increase in nutrients uptake and dry matter content of the crop due to biochar application (Smider and Singh, 2014). Similarly, Rondon *et al*. (2007) reported increase in biological nitrogen fixation in common bean as a result of biochar application. Hossain *et al*. (2010) working on acid soils (pH 4.6) in Camden, south-western region of Sydney, Australia reported application of 10 t ha^{-1} of biochar from waste water sludge to maximize the yield of cherry tomato.

1.3 Study hypothesis

1- There could be differences in the growth, yield and N fixation of the landraces.
2- Rock phosphate application could increase the growth, yield and nitrogen fixation of Bambara groundnut.
3- Application of biochar could increase the growth, yield and nitrogen fixation of the crop.

4- Application of biochar and rock phosphate could interact to increase the growth, yield and N fixation of the crop.

1.4 Objectives of the study

The general objectives of the study the study were:

To study the growth, yield and nitrogen fixation of Bambara groundnut landraces in the study area.

The specific objectives were:

1- To determine a suitable landrace for the growth, yield and nitrogen fixation of Bambara groundnut in the study area.
2- To study the growth, yield and nitrogen fixation of Bambara groundnut at different levels of phosphorus using rock phosphate.
3- To evaluate the effect of biochar application on the agronomic performance of the crop in the study area.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Influence of landrace in Bambara groundnut production

The bunched type of Bambara groundnut matures earlier than those with spreading growth habit (Goli, 1997). Bambara groundnut has a large number of unexploited landraces in Africa and like other grain legumes serve as a cheap source of protein to a large proportion of the population in poor countries of the tropics (Massawe *et al.,* 2005). The plant has numerous nitrogen fixing nodules (Goli, 1997). Landraces vary significantly in yield and N harvest index. Significant correlations were reported between harvest index, and pod and grain yield (Kishinevsky *et al*., 1996). N fixation is not always a clear guide to high pod and grain yield (Kishinevsky *et al*., 1996). Yield in Ghana and Tanzania has been reported to be 10 - 800 kg ha^{-1} and as nitrogen fixing legume the crop contributes to soil fertility maintenance (Hillocks *et al*., 2012). Landraces varied significantly in yield and nitrogen harvest index. Significant correlations were found between harvest index, and pod and grain yield of Bambara groundnut (Kishinevsky *et al*., 1996).

The crop is essentially grown for human consumption and is a good supplement to cereal-based diet (Ouedraogo *et al*., 2008; Alhassan and Egbe, 2013). The red seeded types could be useful in areas where iron deficiency is a problem as they contain almost twice as much as the cream seeds types. The cream or white seeded landraces are more sought after due to their lesser time to cook and command up to 10% premium price than other types (Brink *et al*., 2006; Hillocks *et al*., 2013). The tannin levels were reported to be lowest in cream seeded type, intermediate in red seeded types and highest in black seeded types (Brink *et al*., 2006).

The crop can occasionally produce pods above the ground, and appeared to be wholly dependent on root uptake of calcium (Van der Straten *et al*., 1995; Giller, 2001).

Yield of the crop has been reported to be higher in areas with lesser rainfall but with longer sunshine hours per day which explains the adaptability of the crop do drier areas of the tropics and has been described as more adapted to harsh growing conditions than either cowpea or groundnut. The reduced sunshine hours due to higher precipitation as obtained in the humid and sub humid regions compared to the drier areas showed significant reduction in photosynthesis, LAI and dry matter accumulation and hence lower crop yields (Mkandawire and Sibuga, 2002). Linnemann (1991) reported some landraces to be day-neutral with respect to the flowering behaviour of the crop. Leaf production in the crop was reported to be favoured by longer photoperiods of 14-h than 10-h or 12-h (Linnemann, 1991). Brink (1997) reported the onset of flowering in the crop to be influenced by temperature (constant temperatures of 20.9, 23.4 and 26.2^{o}C) but not by photoperiod (durations of 10.0, 12.5, 13.5 and 16.0 h d^{-1}) and the onset of pod-growth (podding) to be influenced by both the temperature and photoperiod. Linnemann and Craufurd (1994) working on three African landraces at photoperiods (10, 11·33, 12·66 and 16 h d^{-1}) and mean diurnal temperatures (20·2, 24·1 and 28·1°C) reported 2 of the 3 landraces observed to flower irrespective of the photoperiod, whereas flowering was sooner at higher temperatures. However, the third landrace was sensitive to both temperatures and photoperiods and was increased by cooler temperatures at longer photoperiods.

2.2 Influence of phosphorus application on the performance of crops

Phosphorus (P) is the second most limiting nutrient to plant growth after nitrogen (FAO, 2004). It is an essential plant macronutrient that significantly affects plant growth and metabolism (Franco-zorrilla *et al*., 2004; Teng *et al*., 2013). It plays a major role in numerous key molecules, including DNA, RNA and phospholipids. It also, plays an essential role in energy metabolism (Elser, 2012). The P requirement by plants is not primarily because large amounts of P are incorporated into newly synthesised DNA, RNA and membranes, but rather it is required for most biochemical transactions in the cell to proceed (Doerner, 2008). Phosphorus is involved in the regulation of many biochemical and physiological processes. it is an essential building block of cell components such as nucleic acids, membranes and energy sources (Lin *et al*., 2009). Plants require adequate supply of inorganic phosphate for growth and development, while also serving as the major entry point of P into food chain (Hammond *et al*., 2009; Bouain *et al*., 2014). P deficiency restricts crop yields severely (FAO, 2004).

Plants preferentially take up P as orthophosphate, which is up to 80 % immobile and not readily available to roots (Franco-zorrilla *et al*., 2004). Plants acquire P as inorganic phosphate ion through inorganic phosphate transporters in the roots (Lin *et al*., 2009). The maintenance of homeostasis under inadequate P supply is coordinated by enhanced acquisition of external P and by conservation and remobilization of internal P content (Lin *et al*., 2009). P acquisition in plants is achieved by the induction of high-affinity P transport systems, secretion of root exudates to release P from available soil P, alteration of root morphology and architecture by reduced primary root length and increased length and density of branched roots and root hairs. The conservation and remobilization of internal P is facilitated by the alteration of metabolic pathways and by the reallocation and recycling of internal P among different organs or cellular compartments (Lin *et al*., 2009). During the early stage of P deficiency, the demand is satisfied by P translocation from shoot tissues via the phloem (Doerner, 2008).

Phosphorus (P) is widely distributed in nature and occurs, together with nitrogen (N) and potassium (K), as a primary constituent of plant and animal life. However, P availability and nutrition frequently limits crop production in 30-40 % of all arable lands (FAO, 2004; Franco-zorrilla *et al*., 2004).

Despite a large amount of total P in the soil, P availability in often limited as a result of binding and precipitation of P by some cations and conversion into organic compounds in the soil (Lin *et al*., 2009). P content in the soil could be high due to fertilizer application, however, P availability is usually the lowest of the macronutrients and therefore plants often encounter a scarcity of phosphate in both agricultural and natural soils (Teng *et al*., 2013). Deficiency in plant-available P is considered to be a major limiting factor to food production (Arcand and Schneider, 2006).

Phosphorus inputs, must be added under continuous cultivation to either maintain the soil P status of fertile soils or increase the P content of soils with inherent low P fertility (FAO, 2004; Biswas and Narayanasamy, 2006). Maintenance of adequate P concentrations in plants is vital to bring roots into contact with previously unexploited soils (Doerner, 2008). Soil plant-available P occurs in the soil solution as orthophosphate anions, predominantly $H_2PO_4^-$ and HPO_4^{2-} (Arcand and Schneider, 2006). P is taken by plants from the rhizosphere solution as phosphate, primarily in the form of $H_2PO_4^-$. The concentration in the soil solution is often low and consequently the supply of P to the root surface by diffusion is slow. Hence, P is one of the least available mineral element in the soil and frequently limits plant growth (Hammond *et al*., 2009).

Developmental changes in plants in response to P deficiency mostly involve changes in the root architecture that enhance the root surface/soil volume ratio and consequently the ability of the plant to access soil P (Franco-zorrilla *et al*., 2004). Increase in root- to- shoot ratio, number of lateral roots, number and length of root hairs and clusters of lateral roots for soil scavenging are some of the plant responses to soil P deficiency in the rhizosphere (Franco-zorrilla *et al*., 2004).

Soil acidity and low inherent N and P fertility are the major causes of low crop yield in the tropical and subtropical regions of Africa, Asia and Latin America (Formoso, 1999). While N inputs can be obtained from sources such as biological nitrogen fixation, crop residues and other organic sources, P inputs need to be applied in order to improve the soil P status and ensure normal plant growth and adequate yields. Tropical and subtropical soils are predominantly acidic and often extremely P deficient with high P sorption (fixation) capacities. Therefore, substantial P inputs are required for optimum growth and adequate food and fiber production (IAEA, 2002).

The worldwide agriculture depends on external sources of P to increase crop yields. However, P application is neither economically nor ecologically sustainable due to its non-renewable nature (Bouain *et al*., 2014). However, manufactured water soluble fertilizers which are often recommended to correct soil p deficiency are relatively expensive and not affordable to resource poor farmers (IAEA, 2002: FAO, 2004; Biswas and Narayanasamy, 2006; Musa *et al.*, 2012). It is therefore necessary to explore alternative phosphorus inputs such as rock phosphate which are found in most of the region (IAEA, 2002) this could go a long way in addressing the P deficiency and reduce the overall cost of production.

Phosphate rock denotes the product obtained from the mining and subsequent metallurgical processing of P-bearing ores (UNIDO, 1998). Throughout Africa, the region's abundant supplies of rock phosphate form and as yet under exploited resource that, with appropriate processing, could be used to promote the cultivation of legumes and other crops (FAO, 2004). Rock phosphate is a natural material used for the production of P fertilizers (Vassilev and Vassileva, 2003). Global food production is highly dependent on the use of fertilizers produced from rock phosphate (Walan *et al*., 2014). In 2009, approximately 17.6 mt of phosphorus was extracted from phosphate rock mining operations for use as fertilizers (Koppelaar and Weikard, 2013).

Direct application of rock phosphate to soils where suitable could reduce the cost of chemical treatment and minimise environmental pollution (Vassilev and Vassileva, 2003). It could serve as direct source of P for plant production on acidic soils (Nishanth and Biswas, 2008). However, direct application of rock phosphate as P input is not practiced due inadequate knowledge on its agronomic effectiveness (IAEA, 2002). Local sources of phosphate rock are being increasingly recognized for potential use as alternative P fertilizers in regions where the use of conventional P fertilizers is limited due to cost or to mitigate adverse environmental effects (Arcand and Schneider, 2006). However, the major obstacle associated with direct application of rock phosphate to crops is that the phosphate released is often unable to supply adequate plant-available phosphorus for crop uptake (Arcand and Schneider, 2006).

In addition to source, the major factors influencing rock phosphate solubility are soil properties, crop species and management practices. Since the dissolution of rock phosphate releases Ca^{2+}, soils high in calcium do not support rock phosphate dissolution. Similarly, the dissolution of rock phosphate will be favoured if Ca^{2+} is removed from the soil by leaching or plant uptake (Arcand and Schneider, 2006). Phosphorus is generally less available to plant roots due to its low solubility and high capacity for adsorption to soil particles (bounds to minerals rich in calcium, aluminum and iron oxides). Therefore, soil P most be mobilized in to soil solution prior to plant uptake in a process which is largely governed by soil pH (Bouain *et al*., 2014; Maltais-Landry, 2015).

Plant species differ in their P uptake, demand and utilization as well as in their ability to access sparingly forms of P which are unavailable to other plants (Baligar *et al*., 2001; Hocking *et al*., 2001). Legumes such as Bambara are particularly suitable for direct application of rock phosphate. They are effective in dissolving rock phosphate (RP) and in absorbing its dissolution products because of their demand for Ca and the acidifying effect of nitrogen (N) fixation in the soil near the root system (rhizosphere) (Kamh *et al*., 1999; FAO, 2004). High plant root density facilitates the extensive exploration of a large soil volume for P because of the presence of a large number of fine roots per unit of soil volume (FAO, 2004).

It is confirmed that the efficiency of rock phosphate as a source of P is more in acid soils and wetter regions of the world (IART, 1994; Adediran and Sobulo, 1998; Ezekiel and Gabriel, 2006). The soil properties which favour the dissolution of RP are low pH (less than 5.5), low solution concentration of Ca ions, low P fertility levels and high organic-matter content. Other important factors include rainfall, crop species (legumes are particularly suited for the use of RP) and management practices (timing and rate of application) (FAO, 2004).

FAO (2004) reported that RP should not be applied where the soil is pH 6.5 or higher and the annual rainfall should be 750 mm or more. For continual dissolution of rock phosphate, it is important that Ca ion which is the major reaction product of rock phosphate should be removed from the dissolution site or the soil should be maintained at low Ca status. The soils should therefore have adequate cation exchange sites to adsorb the Ca ions released from the rock phosphate or there should be leaching away of Ca from the rock phosphate dissolution site (FAO, 2004). In soils with a low pH (less than 5.5), the exchangeable Ca and Mg will invariably be low (low base saturation) and hence the concentration will be low in soil solution. Soil texture also affects the CEC of the soil. Sandy soils usually have low cation exchange capacity and as such do not provide adequate sink for calcium released from rock phosphate which reduces the dissolution of rock phosphate and its agronomic effectiveness (FAO, 2004).

The Malaysian climatic conditions in terms of rainfall are therefore suitable for the use of PR. Recent publications (Adediran and Sobulo, 1998; Akande *et al*, 1998) reported the efficiency of RP as fertilizer for maize production in southwest Nigeria. Teng *et al*. (2013) reported that plants respond to P deficiency by investing greater proportion of photosynthates in the roots. Sokoto and Singh (2008) reported an increase in both yield and yield components of cowpea with the application of 25 kg RP ha^{-1}.

2.3 Influence of biochar application on the performance of crops

Biochar (charcoal, biomass-derived black carbon) is a stable organic carbon compound obtained after heating biomass to temperatures of between 300-1000^{o}C under limited/zero oxygen concentrations (Rondon *et al*., 2007; Jeffery *et al*., 2011). Biochar is a solid material rich in stable organic carbon formed by the pyrolysis of organic materials under high temperature and oxygen free conditions (Dong *et al*., 2016). Biochar which is a product of thermal decomposition of biomass under oxygen-limited conditions (pyrolysis) (Chen *et al*., 2011)

Biochar which is a charred organic material (charcoal, biochar or black carbon) provides a range of benefits: climate mitigation through carbon sequestration and reduction of nitrous oxide emissions, waste disposal and soil remediation (Raboin *et al*., 2016). Asai *et al*. (2009) reported biochar as a sustainable technology to improve the productivity of highly weathered or degraded tropical soils which is receiving a growing interest by both researchers and farmers. Biochar, the by-product of thermal decomposition of organic materials in an oxygen-limited environment is gaining popularity by both researchers and farmers due to its potential benefits for soil health, increasing crop yield, carbon sequestration and green house mitigation (Hussain *et al*., 2016).

The increase in crop production as a result of biochar application could be attributed to improvement in soil fertility via enhanced availability of basic nutrients (Ca and Mg) in acid soils, increased N retention and N use efficiency and improve soil moisture retention (Liu *et al*., 2013). Biochar could mitigate nitrate leaching by inhibiting the mineralization of organic N to ammonia and hence to nitrate or by adsorbing ammonium or nitrate, thus rendering it less available for leaching (Jin *et al*., 2016).

Biochar has been gaining popularity as a strategy for mitigation of climate change, soil remediation and crop waste disposal (Barrow, 2012; Tang *et al*., 2013). Biochar is known to keep soil applied nutrients in the topsoil within the root zone of most crops thereby increasing the nutrient use efficiency (Lehmann et al., 2003; Barrow, 2012). Biochar as a soil amendment improves crop productivity mainly by increasing the nutrient use efficiency and water holding capacity (Hussain *et al*., 2016). Biochar application reduces soil bulk density, improves soil water holding capacity, enhances soil cation exchange capacity and improves soil aggregation and stability (Dong *et al*., 2016). It has been reported to raise soil pH, increase the water holding capacity of soils and yield performance of crops (Jeffery *et al*., 2011).

Research conducted on Ferrosol to study the effect of biochar application on the agronomic performance of corn showed significant increase in the shoot dry weight of the crop and was attributed to the release of nutrients from the biochar and biochar's liming effect which resulted in increased nutrients availability (Smider and Singh, 2014). Major *et al*., (2010) reported biochar application on highly weathered tropical soils to increase the soil nutrients availability and uptake in maize.

The yield increase as a result of biochar additions could be attributed to its effect on increasing soil pH, improve soil moisture retention capacity and increased nutrients availability (Jeffery *et al*., 2011). Rondon *et al*. (2007) working on common bean (*Phaseolus vulgaris* L.) reported increase in N fixation as a result of biochar application and attributed the increase to K, Ca, P, B and Mo availability. Soil uptake was decreased, whereas the yield and biomass production were increased as a result of biochar application (Rondon *et al*., 2007). Researches have shown that application of biochar to soil can increase crop yields due to increase in soil pH and reduced nutrients leaching (Quilliam *et al*., 2013). Yuan *et al*. (2011) working on the ameliorating effect of biochar on acidic ultisol reported biochar incorporation as soil amendments to increase soil pH, decrease soil exchangeable acidity and exchangeable Al^{3+}. It also increased soil exchangeable base cations and base saturation and had a CEC of 10 to 20 times higher than the soil which increased the soil CEC and retention of Ca^{2+}, Mg^{2+}, K^{+} and $NH4^{+}$.

Biochar application as a soil amendment could be an option to increase crop yields in the humid tropical regions (Major *et al*., 2010). Biochar application enhances crop productivity by improving soil chemical characteristics (nutrient retention and availability), soil physical characteristics (bulk density, water holding capacity and permeability) and soil biological properties. Biochar is also highly recalcitrant to microbial decomposition and thus guarantee a long term benefit for soil fertility (Asai *et al*., 2009). The benefits of using biochar in crop production are often recoded in highly degraded and nutrient poor soils, whereas its application on fertile and healthy soils does not always increase crop yield (Hussain *et al*., 2016).

Biochar application as a soil amendment improves the yield of dryland crops and in acid, poor structured soils. In general, application of biochar at rates <30 t ha^{-1}, increased the yield of dryland crops by 11.0%. The average yield increase as a result of biochar application on dryland crops was higher (10.6 %) than the yield increase in paddy rice which averaged 5.6 % (Liu *et al*., 2013). Raboin *et al*. (2016) reported increase in yield of maize and beans crops due to biochar application and attributed it to the increase in soil pH and decrease in exchangeable aluminum of the soil in the biochar treatments. Similarly, Asai *et al*. (2009) reported decrease in plant uptake of soil nutrients and yield of upland rice due to biochar application despite improved soil physical properties, P availability and nutrient uptake efficiency.

Steiner *et al*. (2007) working on rice crop at Manaus, Amazons, Brazil recorded higher growth and grain yield of the crop where biochar was combined with NPK fertilizer and attributed the increase to the improved soil chemical, physical and biological properties. Liu *et al*. (2013) reported greater increase in crop yield where biochar was applied on acidic soils (pH <5.0) than neutral soils. The yield increase was also observed to be higher (29.5%) on sand than clay soils (16.0 %).

Major *et al*. (2010) working on infertile tropical acidic soils recorded improved crop up to four years after biochar application and attributed the yield increase to improved crop nutrition which resulted from improved pH and base cation retention in the rooting zone. This indicates that a single biochar application may provide benefits over several cropping seasons. Van Zwieten *et al*. (2010) reported biochar to reduce N fertilizer input while maintaining productivity which is as a result of increased N retention. Jeffery *et al*. (2011) reported the most important mechanisms that could explain the crop yield increase as a result of soil amendment using biochar to be the liming effect of biochar, improved water holding capacity of the soil along with improved nutrient availability.

Hossain *et al*. (2010) working on acid soils (pH 4.6) in Camden, south-western region of Sydney, Australia reported application of 10 t ha^{-1} of biochar from waste water sludge to maximize the yield of cherry tomato and attributed the increase in the yield of the crop to the combined effect of increased nutrient availability (N and P) and soil electrical conductivity recorded in the biochar applied treatments. Yamato *et al*. (2006) working on the effects of charred bark of *Acacia mangium* application as soil amendment for the cultivation of cowpea, maize and peanut in South Sumatra, Indonesia recorded significant increase in the yield of maize and peanut as a result of biochar application. Biochar application was also found to decrease the exchangeable Al^{3+} content of the soil. However, it increased the soil pH, total N and available P contents, cation exchange capacity, amounts of exchangeable cations and base saturation.

Pratiwi and Shinogi (2016) working on rice husk biochar observed decrease in soil bulk density and an increase in saturated hydraulic conductivity, total pore volume and available soil water content as a result of biochar application. The shoot height was slightly higher in the biochar applied plots.

2.4 Biological nitrogen fixation and its significance in legumes

Biological N fixation is the key to sustainable N input into agricultural ecosystem (Salvagiotti *et al*., 2008; Lindström *et al*., 2010). It offers a more environmentally sound and sustainable source of N into cropping systems (Crews and Peoples, 2004). Biologically fixed N is used directly by legumes and is therefore a more sustainable way to provide N to plants while minimizing losses to the environment (Graham and Vance, 2000). In the tropics, legumes play a major role as an integral part of agricultural systems. The ability to fix nitrogen offers an important alternative to the use of inorganic fertilizers that are costly and unavailable in the local markets (Ndakidemi *et al*., 2006).

Biological nitrogen fixation is a natural process of significant importance in world agriculture (Herridge *et al*., 2008). After photosynthesis, N_2 fixation is probably the most important biologically mediated process on earth (Unkovich *et al*., 2008). The demand for accurate determination of global inputs of biologically-fixed nitrogen is strong and will continue to be fueled by the need to understand and effectively manage the global N cycle (Herridge *et al*., 2008). Rhizobia are soil bacteria that enter into a symbiosis with leguminous plants, producing root out growths (nodules) within which the bacteria convert atmospheric nitrogen into ammonia, that is made available to the plants in a process known as biological nitrogen fixation (Downie, 2007). Biological N fixation (BNF) is a process which involves the reduction of atmospheric dinitrogen to ammonia (NH_3) (Giller and Wilson, 1991). The most important nitrogen fixing agents in agricultural systems are the symbiotic association between crop and forage/fodder legumes and rhizobia. In a related study researches have shown that all bacteria derived from peanut and Bambara groundnut were capable of inducing nodules in each other and cowpea (Singleton *et al*., 1992). Poor nodulation in legumes could be as a result of low indigenous rhizobium population or due to inefficient strains of native rhizobia (Appunu and Dhar, 2006).

The ability to fix atmospheric nitrogen allows legumes to grow and survive in soils with low nitrogen content as is the case in most of the production regions, the crop performs satisfactorily in marginal soils that are uneconomical to produce other crops and at the same time reduce losses from denitrification, volatilization and leaching (Roskoski *et al*., 1986; Yakubu *et al*., 2010). Although the crop is grown in areas where cowpea and groundnut are grown, the crop is considered to have an advantage over those crops in its adaptation to poor soils and drought (Hillocks *et al*., 2012).

The process of N_2 fixation is strongly related to the physiological state of the host plant and is not expected to be at its optimum if limiting factors (unfavorable soil pH, nutrient deficiency, mineral toxicity, insufficient or excessive soil moisture, inadequate photosynthesis and plant disease) imposed limitation on the vigor of the host plant (Brockwell *et al*., 1995; Peoples *et al*., 1995; Thies *et al*., 1995; Zahran, 1999). Inadequate photosynthesis as occurred in the wetter tropics and soil acidity are typical environmental stresses faced by legume nodules and rhizobium (Bottomley, 1991; Walsh, 1995; Zahran, 1999). Nitrogen fixation depends on photosynthesis to provide ATP for energy and carbon compounds as electron donors (Paul and Clark, 1996; Belnap, 2001). The bacterial nitrogenase enzymes are oxygen sensitive and require high ATP levels to drive the reaction and these could explain why good soil aeration and sufficient photosynthesis are necessary not only for the legume but also for the rhizobium (Downie, 2005). The blood-red color in the nodules is due to high levels of haemoglobin referred to as leghaemoglobin since they are peculiar to legumes and are essential for symbiotic nitrogen fixation in the root nodules of legume plants (Downie, 2005).

Factors influencing nitrogen fixation include differences between cultivars in different climatic zones, soil types and weather conditions. Plant dry matter yield is the driving factor behind nitrogen fixation (Unkovich and Pate, 2000; Carlsson and Huss-Danell, 2003; Herridge *et al*., 2008; Yang *et al*., 2010). In some soils other factors such as soil pH, mineral toxicities or nutrient deficiencies could influence N_2 fixation without directly affecting the plant growth (Reddy and Tanner, 1980; Nambiar, 1985). The rate of nitrogen fixation ranges between 3-10 kg shoot N ha^{-1} per day (Unkovich and Pate, 2000). The amount of N_2 fixed by legume is between 15-25 kg shoot N for every tonne (t) of shoot dry matter with an average of 20 kg shoot N per tonne of shoot dry matter (Unkovich *et al*., 2008). Among the major attributes of Bambara groundnut is its ability to fix nitrogen (Linnemann, 1991). Hillocks *et al*. (2012) reported that the crop contributes 20-100 kg N ha^{-1}.

Grain legumes are reported to fix 15–210 kg N ha^{-1} seasonally in Africa (Dakora and Keya 1997). Yakubu *et al*. (2010) worked on legume varieties in the North-eastern region of Nigeria and reported the crop to fix 32.53kg N ha^{-1}. Kishinevsky *et al*. (1996) reported N fixed in the crop at 1.2 g per plant, which was 80% of the total N accumulated in the plants at 130 days.

Nitrogen (N) balance studies have been used to predict the contribution of grain legumes to the soil or crop in rotation or intercropping (Singh *et al*., 2003). It depends on the difference between the inputs and outputs of N in the system. N balance is the quantity of N fixed minus quantity of N removed in harvested grain (Haynes *et al*., 1993) and is a measure of the net N contribution of N fixing legumes to soil N and is reported to be negative where N harvest index is greater than N derived from atmospheric fixation (Haynes *et al*., 1993).

2.5 Influence of soil acidity on crop production

Acid soils (Ultisols and Oxisols) are widespread in Southeast Asia. They are found scattered in the low and upland areas of Malaysia, Thailand and Indonesia (Shamshuddin *et al*., 2009). In Malaysia, the pH of mineral soils ranges from 3 to 5, with Ultisols and Oxisols ranging from 4 to 5. Ultisols and Oxisols are highly weathered soils found in areas subjected to extreme temperatures and rainfall throughout the year which resulted in leaching of basic cations and accumulation of sesquioxides. The soils are reddish in color due to presence of hematite and their profiles are deep sometimes up to a depth of 2m. They are generally regarded as infertile due to low soil pH, low basic cations, low available P and high Al content at a level which is toxic to crops. The soils also lack organic matter which retains plant nutrients and improve the soil structure (Shamshuddin *et al*., 2011). Soil pH affects bioavailability of plant nutrients and so, indirectly plant growth and yield (Goulding, 2016). Al toxicity restricts root growth by inhibiting cell division, cell elongation or both whereas, Ca and/or Mg deficiency in the area further inhibits the root growth (Shamshuddin and Fauziah 2010). Similarly, Shamshuddin *et al*. (2009) reported high Al content in the soil to lower yields of corn and groundnut which are often planted as intercrops during the early growth of oil palm and rubber plantations. Similarly, the yield of rubber, cocoa, oil palm and other fruit trees recorded mixed results.

Tropical acidic soils are deficient in range of plant nutrients, particularly phosphorus. The performance of water soluble P fertilizers on these soils is low due to high P fixation which resulted from high Fe and Al contents of the soils (Corrêa *et al*., 2005; Basak and Biswas, 2016). Increasing soil acidity causes decrease in base saturation and CEC, with base cations such as Ca and Mg moving down the soil profile as a results of heavy rain (Blake *et al*., 1999).

2.6 Summary of the literature review section

The chapter provides detailed information on the influence of landrace in Bambara groundnut production; the description of the crop, economic importance, adaptation and some of the previous work on the crop. The importance of phosphorus application on the performance of the crop was also discussed; the role of P on the growth and yield of crops, phosphorus acquisition, P deficiency symptoms, rock phosphate description, potentials and dissolution. The influence of biochar application on the performance of crops; biochar description, importance, effect on soil properties, rates of application and previous findings on its effect in crop production. The chapter also highlighted on biological nitrogen fixation and its significance in legumes; the role of rhizobia, factors affecting N fixation, the amount of N fixed in legumes and N balance. The chapter also highlighted soil acidity in the study area as it affects crop production; the origin and distribution of acid soils (Oxisols and Ultisols), fertility problems associated with acid soils, the effect of soil pH on bioavailability of plant nutrients, the effect of Al toxicity growth and nutrient deficiencies.

CHAPTER THREE

3. MATERIALS AND METHODS

The objectives of the research were evaluated using three experiments in both the field and screenhouse. This chapter describes the methodology for the experiments and where there is difference between the field and the screenhouse experiments, subheadings are used for further clarification. Similarly, the treatments, experimental design, data collection and data analysis procedure used are also presented based on the experiment using subheadings as experiment 1, 2 and 3:

Experiment 1: Field Evaluation of three Bambara groundnut landraces for growth variables, yield, and N fixation.

Experiment 2: A screenhouse studies on the influence of Christmas Island Rock Phosphate levels on the growth variables, yield and N fixation of Bambara groundnut landraces.

Experiment 3: Field experiments on the growth variables, yield and N fixation of Bambara groundnut landraces as influenced by biochar and rock phosphate levels.

3.1 Experimental site

3.1.1 Experiments 1 & 3 (Field experiments)

The experiments were carried out at the Field Research Centre of the Crops For the Future (CFF), located adjacent to The University of Nottingham Malaysia Campus, Semenyih, Selangor Malaysia (Figure 3.1.1). The area is located on Latitude 2.931083 and Longitude 101.878323 at an elevation of 42m above sea level. The climate of the area is sub humid tropics with mean annual rainfall of 3000 mm. The soil of the experimental site is an Ultisols (Rengam soil series, a clayey, kaolinitic, isohyperthermic Typic Paleudult) (Fardeau and Zapata, 2002; Shamshudden *et al*., 2009). The experimental site was planted with oil palm plantation and was cleared prior to land preparation. Experiment 1 was carried out from October, 2013 to February, 2014. Whereas, Experiment 3 was carried out from February to June, 2015 (first trial) and repeated from August to December, 2015 (second trial). The total rain received during Experiments 1 and 3 were 643, 853.6 and 1225 mm, for experiment 1, first trial of experiment 3 and second trial of experiment 3, respectively (Figure 3.1.2, 3.1.3 and 3.1.4). The mean maximum and minimum temperatures for the first and second trial of experiment 3 were 33.5 and 22.8^{O}C, and 33.0 and 22.8, respectively. The mean maximum and minimum relative humidity recorded during the first and second trial of experiment 3 were 97.0 and 50.5 % and 98.5 and 54.1 %, respectively. The mean light intensity was 0.197 and 0.174 kw m^{-2}, respectively for the first and second trial of experiment 3.

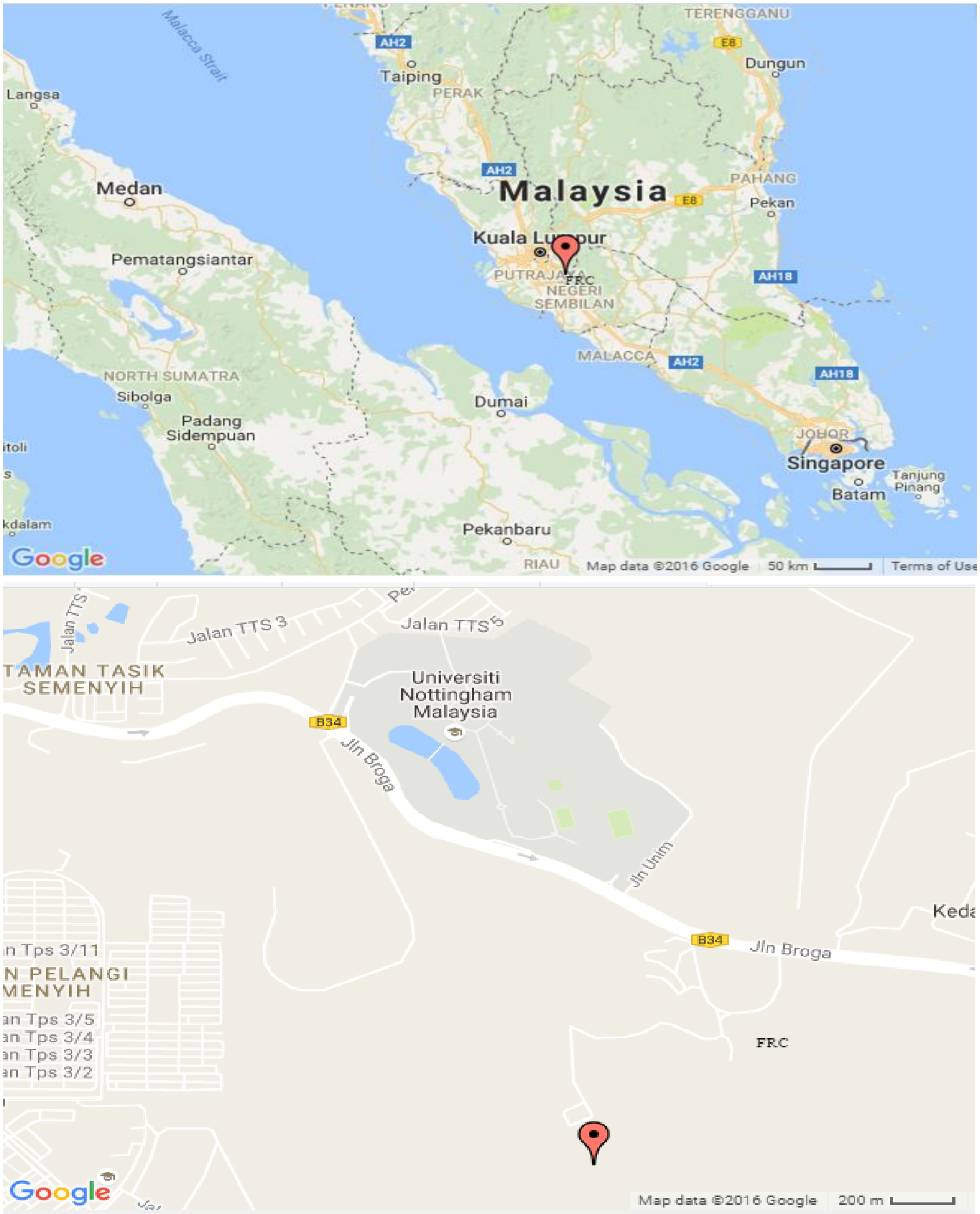

Figure 3. 1. 1: Geographical location of the experimental site.
Source: Google Maps 2016.

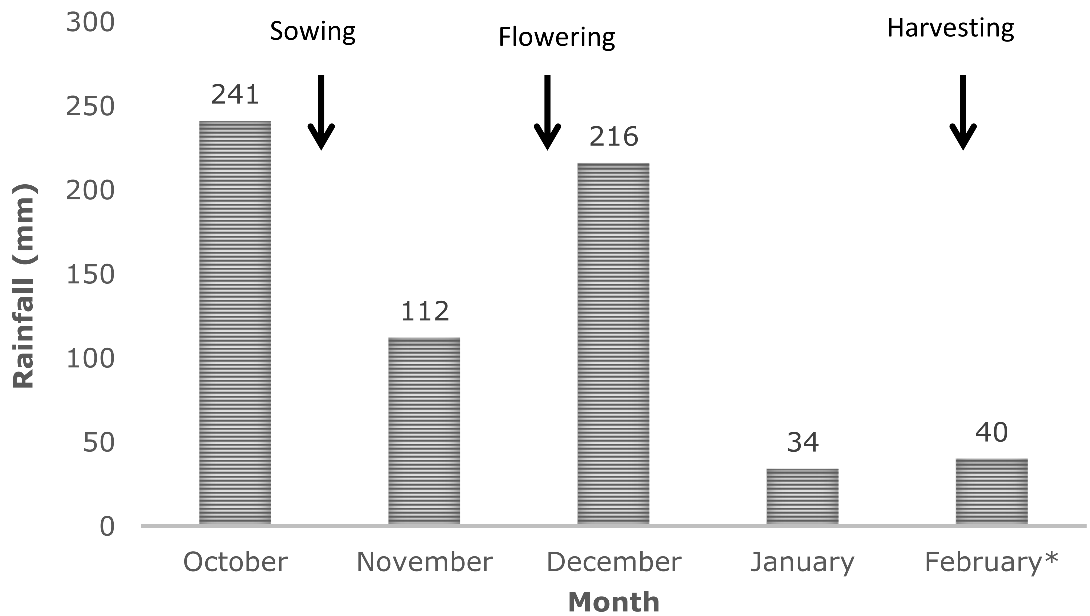

Figure 3. 1. 2: Monthly rainfall (mm) received at the experimental site from October, 2013 to February, 2014. Total water input = 643 mm, * supplied through irrigation

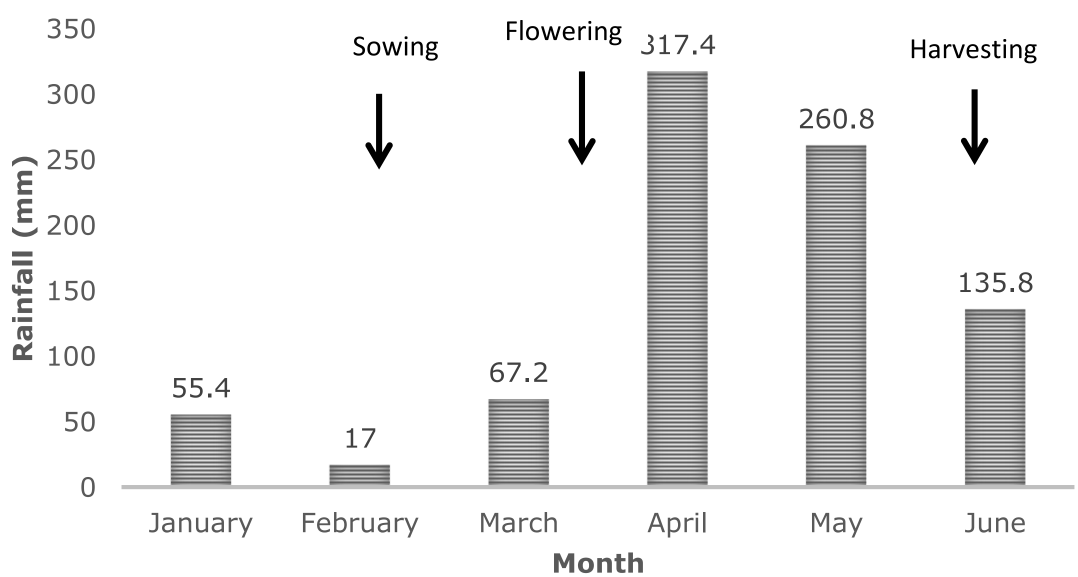

Figure 3. 1. 3: Monthly rainfall (mm) received at the experimental site from January-June, 2015. Total rainfall received = 853.6 mm

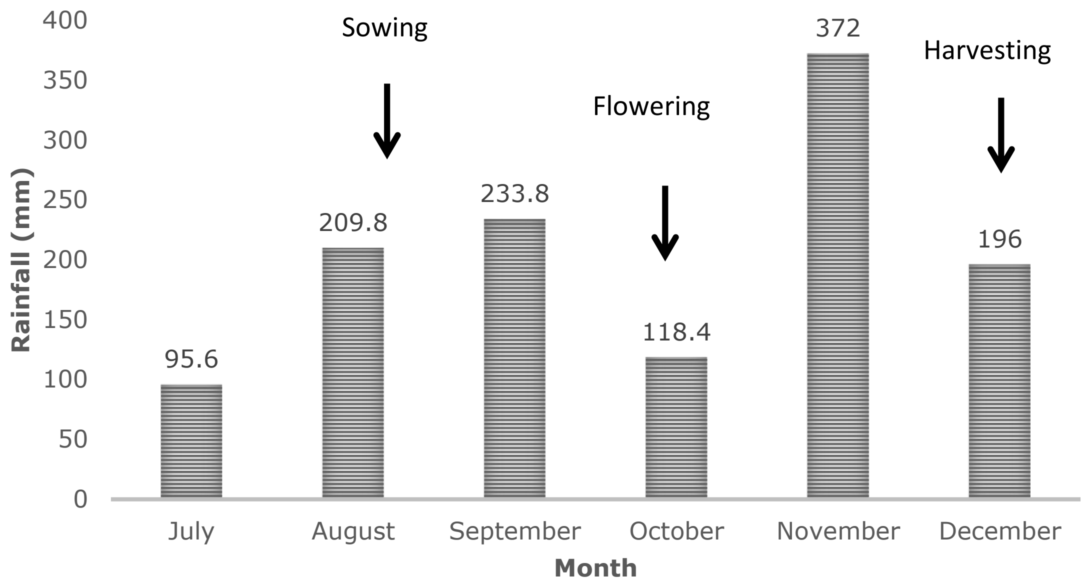

Figure 3. 1. 4: Monthly rainfall (mm) received at the experimental site from July-December, 2015. Total rainfall received= 1225 mm

3.1.2 Experiment 2 (Screenhouse experiment)

The experiment was carried out in the Screenhouse of The University of Nottingham Malaysia Campus, Semenyih Selangor Malaysia.

3.2 Soil sampling and analysis

Composite soil samples were collected from nine randomly selected points within the experimental site at 0-20 cm depth using soil auger. The samples were bulked, air-dried and sieved. The bulked soil sample for each experiment was analysed for physico-chemical properties at Applied Agricultural Resources (AAR) Laboratories Sdn Bhd. Malaysia. The nitrogen content was determined using Micro Kjeldahl digestion techniques as suggested by Unkovich *et al*. (2008). The cation exchange capacity was determined by 1M NH_4OA_C buffered at pH7. The cations (Ca, Mg, K and Na) in the NH_4OA_C solution were determined by atomic absorption spectrophotometry (AAS). Exchangeable Al was extracted by 1M KCl and the Al in the extract was determined by AAS. The results of the soil analysis for the field and the screenhouse experiments are presented in Table 3.2.1.

Table 3. 2. 1: Physico-chemical properties of the soil used in the field and screenhouse experiments

Properties	Field soil		Screenhouse soil	
Chemical Properties				
pH (H_20)	4.72	Very strongly acidic	4.70	Very strongly acidic
Available P (ppm)	11.5	Low	1.8	Low
Carbon (%)	0.72	Low	0.36	Low
Total N (%)	0.08	Low	0.05	Low
Exchangeable cations (meq%)				
K	0.04	Low	0.09	Low
Ca	0.58	Low	0.54	Low
Mg	0.11	Low	0.07	Low
Na	0.01	Low	0.01	Low
Al	0.67	High	0.56	High
CEC	4.0	Low	3.4	Low
Physical properties				
Sand (g kg^{-1})	730		560	
Silt (g kg^{-1})	50		120	
Clay (g kg^{-1})	220		320	
Soil texture	Sandy clay loam		Sandy clay loam	

3.3 Experimental materials

3.3.1 Description of the landraces

Three landraces (Kaaro, Ex-Sokoto and NN-1 both from Nigeria) were used for the first field evaluation after which only two landraces (Ex-Sokoto and Kaaro) were maintained for the rest of the studies. The description of the landraces used is presented in Table 3.3.1.

3.3.2 Description of the rock phosphate used during the experiment

The rock phosphate used was Christmas Island Rock Phosphate (CIRP) which was sourced from the Input Shop, Semenyih. The description of the rock phosphate is presented in Table 3.3.2.

3.3.3 Source of the biochar used during the experiment

The biochar used was sourced from Ladybird Organic Farm, Semenyih as presented in Table 3.3.3. The properties of the biochar are presented in Table 3.3.4.

Table 3. 3. 1: Description of the landraces used in the experiments

Landrace	Source	Duration (days)	1000grain weight	Seed colour
Ex-Sokoto	Sokoto State, North-Western Nigeria	100-120 days	790 g	Cream white with black eye
Kaaro	Niger State, Central Nigeria.	110-120 days	980 g	Cream
NN-1	Kano State, North-Western Nigeria	100-120days	1160 g	Black stripped

Characterization was carried out using IPGRI Descriptors for Bambara groundnut (IPGRI, IITA, BAMNET, 2000)

Figure 3. 3. 1: Seeds of the two landraces maintained for experiment 2 and 3.

Table 3. 3. 2: Characteristics of Christmas Island Rock Phosphate (CIRP)

Name	Christmas Island Rock Phosphate
Total P content	32 %
Solubility (Neutral ammonium citrate)	3.6 %
Origin	Christmas Island, Australia
Source	Christmas Island Rock Phosphate Distribution Company Shah Alam, Malaysia
Texture	Fine powder
Color	Brown

Table 3. 3. 3: Source of the biochar used in the field trial

Name	Rice Biochar
Source	Ladybird Organic Farm, 43500 Jalan Broga, Semenyih, Selangor, Malaysia
Texture	Powdered form

Table 3. 3. 4: Physico-chemical properties of the biochar used in the experiment

Properties	Values
pH (H20)	6.73
Total P_2O_5 (%)	0.14
Carbon (%)	18.40
Total N (%)	0.27
S (%)	0.07
Fe (%)	0.03
K_2O (%)	0.48
CaO (%)	0.18
MgO (%)	0.13
Na (%)	0.01
Al (ppm)	82.0
C/N ratio	68.4
Total ash (%)	62.3
Conductivity(µs/cm)	1728.5

3.4 Treatments and experimental design

3.4.1 Experiment 1

The treatments consisted of three Bambara groundnut landraces (Ex-Sokoto, Kaaro and NN-1). Some important attributes of the landraces are presented in Table 3.3.1. The treatments were laid out in a randomized complete block design replicated three times. The gross plot size was maintained at 3.0 m X 2.5 m (7.5 m^2) while the net plot area was maintained at 2.6 m X 1.5 m (3.9 m^2). The row-to-row (inter-row) spacing was maintained at 50 cm distance while plant-to-plant (intra-row) spacing was at 20 cm. The land was ploughed, harrowed and leveled prior to sowing using a tractor, plots were demarcated and ridged at 50 cm spacing.

Figure 3. 4. 1: A replicate showing the arrangement of the three landraces in a completely randomized design during October-2013 to February-2014 growing season

3.4.2 Experiment 2

The treatments consisted of factorial combination of two Bambara groundnut landraces (Ex-Sokoto and Kaaro) and four rock phosphate levels [0, 20, 40 and 60 kg P_2O_5 ha^{-1}, the equivalent of 0, 555.6, 1111.1 and 1666.7 kg ha^{-1} of Christmas Island Rock Phosphate [32 % P_2O_5, 3.6 % solubility using 2 % Neutral Ammonium Citrate (NAC)] applied at 0.28, 0.56 and 0.84 g kg^{-1} of soil, respectively based on the dry weight of one-hectare furrow slice (15-17 cm deep) estimated to be about 2 000 000 kg soil.] making a total of eight treatment combinations. The treatments were laid out in a completely randomized design (CRD) replicated three times. The pots were arranged at a field spacing of 50 cm X 20 cm for between and within the pot rows, respectively.

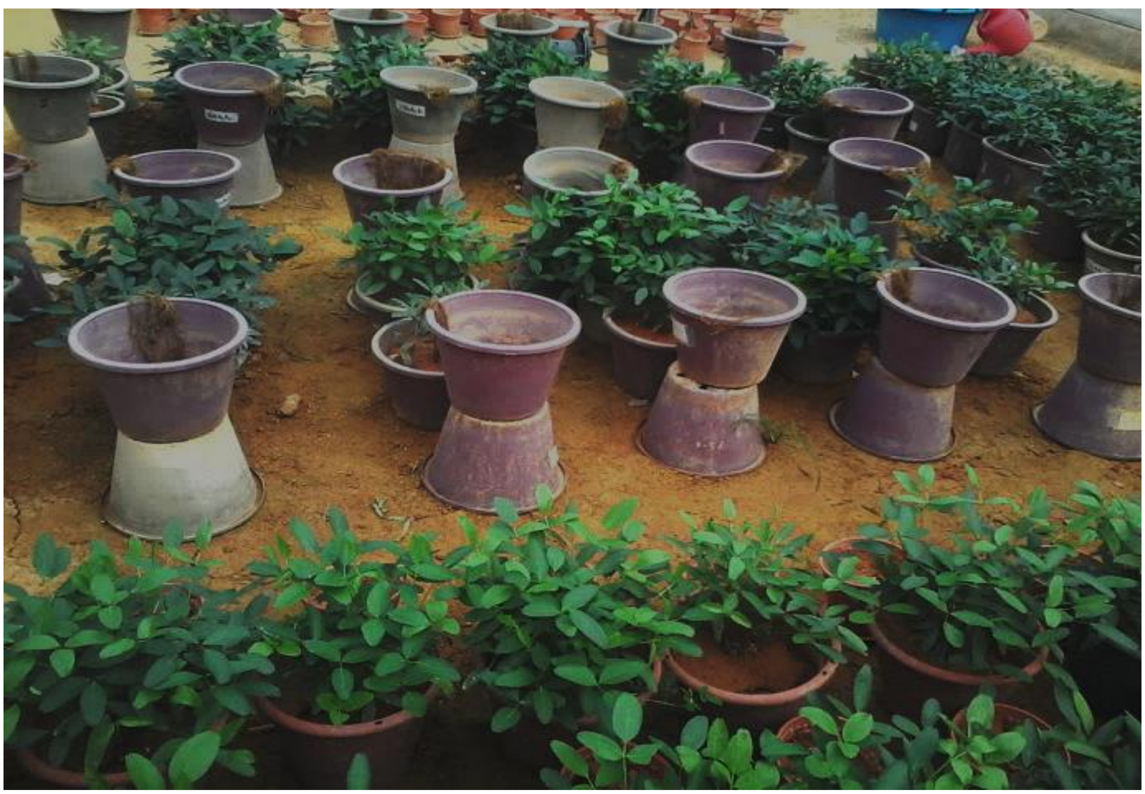

Figure 3. 4. 2: The plot layout of the screenhouse experiment showing the second destructive sampling for root studies at 8 weeks after sowing in the Screenhouse of The University of Nottingham Malaysia Campus

3.4.3 Experiment 3

The treatments consisted of factorial combination of two Bambara groundnut landraces (Ex-Sokoto and Kaaro), two biochar levels (0 and 10 t ha^{-1}) and four rock phosphate levels [0, 20, 40 and 60 kg P_2O_5 ha^{-1}, the equivalent of 0, 555.6, 1111.1 and 1666.7 kg ha^{-1} of Christmas Island Rock Phosphate [32 % P_2O_5, 3.6 % solubility using 2 % Neutral Ammonium Citrate (NAC)]] making a total of sixteen treatment combinations. The treatments were laid out in a randomized complete block design (RCBD) replicated three times. The gross plot size was maintained at 3 m X 3 m (9 m^2) while the net plot area was maintained at 2.6 m X 1.5 m (3.9 m^2). The crop was planted on twin-rows spaced at 50 cm within the rows and 1m apart between the rows. The plant-to-plant (intra-row) spacing was at 20 cm.

Figure 3. 4. 3: Field layout of experiment 3 showing the rows of the no biochar applied plots at 3 weeks after sowing

Figure 3. 4. 4: Field layout of experiment 3 showing the rows of the biochar applied plots at 3 weeks after sowing

Figure 3. 4. 5: Field layout of the second trial of experiment 3 showing the crop at 4 weeks after sowing

Figure 3. 4. 6: Field layout of the second trial of experiment 3 showing the crop at 6 weeks after sowing

Figure 3. 4. 7: Field layout of the second trial of experiment 3 showing the crop at 8 weeks after sowing

3.5 Cultural practices

The cultural practices for both the field and the Screenhouse experiments were mostly similar. However, where there is difference between the two subheadings are used for further clarification.

3.5.1 Seed treatment

For all the trials, the seeds were soaked overnight prior to planting. The soaked seeds were pre-dried and treated using combination of fungicide and insecticide at planting.

3.5.2 Soil preparation

Experiment 1:

The land was ploughed, harrowed and leveled prior to planting using a tractor, after that, plots were demarcated and ridged at 50 cm spacing for the evaluation of the landraces.

Experiment 2:

The soil was collected, air-dried and thoroughly mixed, 9.5 kg of the air-dried soil was used for each pot and the pots were arranged at a field spacing of 50 X 20 cm.

Experiment 3:

The land was ploughed, harrowed and leveled prior to planting using a tractor, after that, plots were demarcated and 1m wide rows were constructed and the crop was planted on twin-rows at 50 cm spacing between the rows.

3.5.3 Biochar application

The biochar was applied at the uniform rate of 10 t ha^{-1} for the biochar treatments on the field. The biochar applied was thoroughly incorporated in to the top 20 cm soil depth prior to sowing.

3.5.4 Rock phosphate application

In the field, the P_2O_5 equivalent of 0, 20, 40, and 60 kg ha^{-1} was broadcasted and incorporated uniformly in to the soil as per treatment to a depth of 20 cm using tractor so as to facilitate greater dissolution. However, for the pot experiment, the rock phosphate treatment equivalents (0.28, 0.56 and 0.84 g kg^{-1}) were thoroughly mixed with the soil manually prior to planting.

3.5.5 Sowing

Sowing was carried out on ridges spaced at 50 cm distance. A within the row distance of 20 cm was maintained for all the varieties. Two seeds per hole were planted at a depth of 3-5 cm using dibbling method both in the field and the Screenhouse experiments.

3.5.6 Weed control

Weeds were controlled manually using hoe before flowering after which hand pulling was maintained.

3.5.7 Fertilizer application

Nitrogen (N) and potassium (K) fertilizers were applied at the rate of 20 and 60 kg N and K_2O ha^{-1}, respectively using Urea (46% N) and Muriate of potash (60% K_2O) as nutrient sources. P was applied as prescribed by the treatment using Christmas Island Rock Phosphate (32 % P_2O_5, 3.6% solubility using 2% Neutral Ammonium Citrate). All the P_2O_5 levels were computed using the NAC solubility of 3.6 %. The fertilizers were applied and mixed thoroughly with the soil before sowing.

3.5.8 Pest and disease control

A combination of fungicide (Mancozeb 80% w/w at the rate of 2.5 kg ha^{-1}) and insecticide (Cypermethrin 5.5% at the rate of 800 ml ha^{-1}) was applied at 4, 6 and 8 weeks after sowing to control insects and other diseases observed during the trial.

3.5.9 Harvesting

Harvesting was carried out manually at physiological maturity (when the leaves turn yellow and the parenchymatous layer surrounding the embryo had disappeared) using a hand hoe for the field experiments and a knife for the pot experiments. The tap root below the pod bearing layer was severed at 10-15 cm depth and the crop was gently pulled out of the ground. After harvesting, the pods were threshed, shelled and air-dried to constant weight in the shade. Samples from the grain, haulm and shell were collected for further drying in the oven at 70°C for 72 hours.

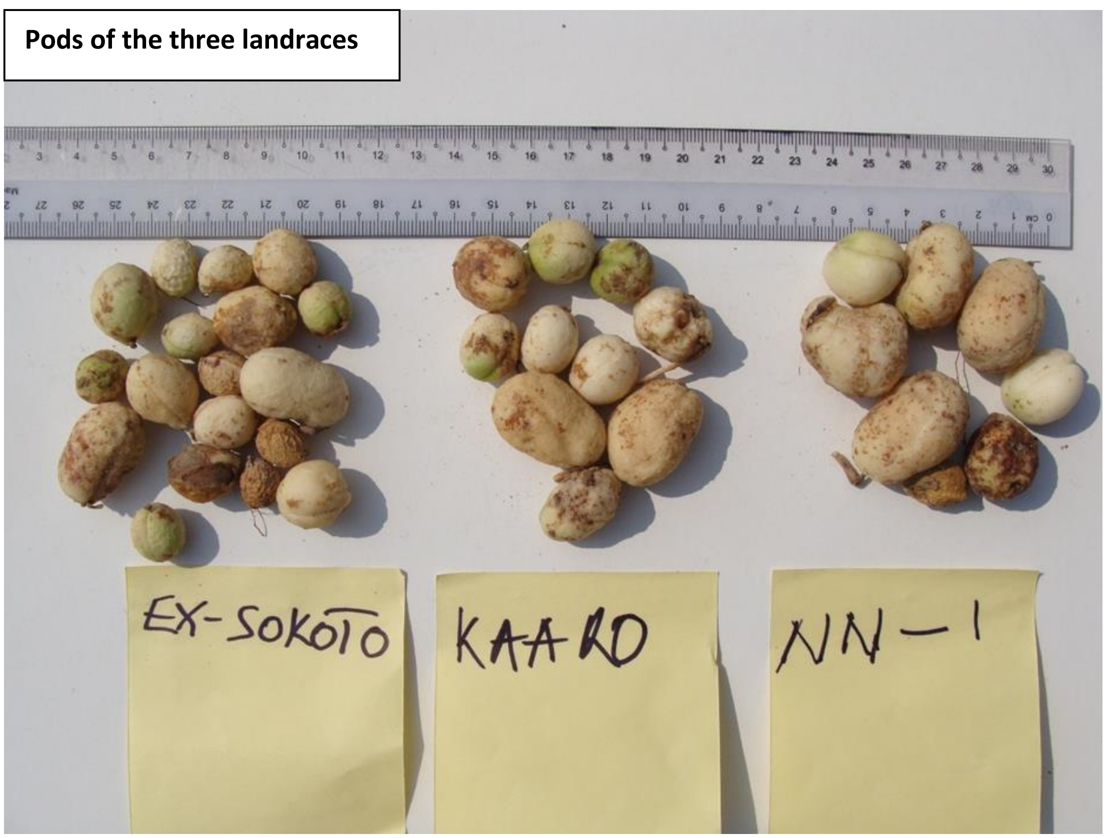

Figure 3. 5. 1: Pods of each of the three landraces grown in experiment 1.

Figure 3. 5. 2: Pods of the two landraces at harvest in the screenhouse, The University of Nottingham, Malaysia Campus.

3.6 Data collection

For experiments 1 and 3 (field experiments), the data for the growth parameters were taken from five plants sampled and tagged at the beginning of the experiment, whereas the data for the yield and other yield components were taken from the entire plants within the net plot area. However, for experiment 1 (screenhouse experiment), the measurements were carried out on the plants in the pots directly. The measurements taken for each experiment are listed below:

Experiment 1

Data were collected on plant height, number of leaves, leaf chlorophyll content (SPAD Value), leaf area index (LAI), number of pods plant^{-1}, pod weight, shell weight, grain weight, haulm weight, total dry weight, shelling percentage, harvest index, N concentration, N content, N-harvest index (NHI), total N content, percentage N derived from the atmosphere ($\%\, Ndfa$), N fixed and N balance.

Experiment 2

Data were collected at 4 and 8 weeks after sowing on plant height, number of leaves, leaf area index, chlorophyll content (SPAD value), shoot dry weight, plant dry weight, root length, root volume, root diameter, root dry weight, root surface area and root/shoot ratio. Data was also collected on number of pods per plant, number of grains per plant, 1000-grain weight, pod weight, grain weight, shelling percentage, haulm weight, total plant dry weight, harvest index, N concentration, N content, N harvest index, % nitrogen derived from the atmosphere (% ndfa), N fixed in the shoot, N fixed in the whole plant, shoot soil N uptake and N balance.

Experiment 3

Data were collected at 4, 6 and 8 weeks after sowing on plant height, number of leaves, leaf area, leaf area index, chlorophyll content (SPAD value), normalised difference vegetation index (NDVI), leaf photosynthesis, stomatal conductance, transpiration and days to 50 % flowering. Data were also collected on number of pods per plant, 1000-grain weight, pod weight, grain weight, shelling percentage, haulm weight, total plant dry weight, harvest index, N concentration, N content, N harvest index, % nitrogen derived from the atmosphere (% ndfa), N fixed in the shoot, N fixed in the whole plant, shoot soil N uptake and N balance.

The procedure for the data collection in all the experiments is as described below. Differences between the field and the screenhouse experiments in the data collection were also highlighted under the subheadings.

3.6.1. Plant height

Plant height was measured at 4, 8, and 12 weeks after sowing using meter rule. Five (5) plants were sampled and tagged for the measurement of plant height and other parameters on the field, whereas, in the screen house experiment, the stands in the pots were measured and recorded against each treatment

3.6.2 Number of leaves

Number of leaves per plant was counted at 4, 8 and 12 weeks after sowing using the tagged plants above. The average number of leaves per plant was recorded.

3.6.3 Leaf area

Leaf area was measured using LI-3100C Area Meter, LI-COA® Biosciences for the experiment in the Shade house only. For the field experiment, a non-destructive Leaf area assessment was used and was estimated using the measurement of the middle leaflet width and length according to the procedure of Molosiwa (2012):

Leaf Area = 0.74 x 3 x number of leaves x (leaflet Length x Width x $\pi/4$)

3.6.4 Leaf area index

The ratio of the plant leaf area by the ground area occupied was measured using AccuPAR model LP-80 PAR/LAI Ceptometer, Decagon Devices, Inc. however for the second and third experiments, the ratio of the plant leaf area by the ground area occupied was measured by dividing the leaf area obtained above by the spacing allocated to the plant.

3.6.5 Normalised difference vegetation index (NDVI)

The normalised difference vegetation index (NDVI) is a measurement of the vegetation cover on the land surface area and was measured using CROP SCAN, GreenSeeker® handheld crop sensor, Trimble, Sunnyvale, CA, USA. This was measured in the field experiments only. Two measurements were taken above two different centre rows of each plot on opposite edge, by walking at an even pace along the length of the plot. A constant height of 1m above the top of the canopy was maintained by tying a string on the underside of the instrument. The NDVI for each pass was recorded and the average for each plot was taken.

3.6.6 Leaf chlorophyll content

Plant leaf chlorophyll content was measured using SPAD Chlorophyll Meter, SPAD 502 plus, KONICA MINOLTA, INC. Made in Japan.

3.6.7 Photosynthetic characteristics

Photosynthesis, stomatal conductance and transpiration were measured on the field using LI-6400XT portable photosynthesis system at 4, 6, and 8 weeks after sowing. Five plants were sampled and tagged for the measurements. A newly opened fully extended leaf was used for the measurements at all the sampling dates.

3.6.8 Days to flowering

Number of days to 50% flowering was recorded for each treatment. A treatment was considered at 50 % flowering when half of the plants within the net plot area had at least one flower.

3.6.9 Number of pods per plant

Number of pods per plant was counted from the tagged plants at harvest and the average number of pods per plant was recorded.

3.6.10 Haulm yield

After threshing, the haulms were heaped and allowed to a constant weight in an open airy shade. Sampling and further drying was carried out in the oven. The dried haulms were weighed using weighing balance.

3.6.11 Pod yield

The pods were threshed two days after lifting from the soil and then spread to dry to a constant weight. Samples were further dried in an oven and weighed using weighing balance.

3.6.12 Grain yield

The weighed pods above were shelled manually following drying to carefully separate the kernels from hulls. The grains were weighed using weighing balance.

3.6.13 Shell weight

The shell weight constituted the weight of the pod wall after the grains had been removed.

$$Shell\ weight = Pod\ weight\ -\ Grain\ weight$$

3.6.14 Stover weight

The stover weight constitutes the weight of the entire crop residue after removing the grain and was obtained by adding the weight of the haulm and the shell.

$$Stover\ weight\ = Haulm\ weight + Shell\ weight$$

3.6.15 Total dry weight

The total dry weight constitutes the weight of the entire shoot of the crop. In this research, the total dry weight was determined by adding the weight of the pod and haulm yield of the crop.

$$Total\ dry\ weight = Pod\ weight + Haulm\ weight$$

3.6.16 Harvest index

The proportion of grain yield to the total dry weight usually expressed in percentage (Turner, 2004) was estimated by dividing the grain yield by the total dry matter (haulm + pod) multiplied by hundred.

$$Harvest\ index\ (HI) = \frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ dry\ weight\ (pod + haulm)\ (kg\ ha^{-1})}\ X\ 100$$

3.6.17 Shelling percentage

The proportion of grain to the pod yield in percentage was estimated by dividing the weight of the grain by the total pod weight (hulls + grains) multiplied by hundred.

$$Shelling\ percentage\ (SP) = \frac{Grain\ yield\ (kg\ ha^{-1})}{Pod\ yield\ (kg\ ha^{-1})}\ X\ 100$$

3.6.18 1000-grain weight

After shelling 1000-grains were randomly selected from each treatment and their weight expressed as to a near 0.00g

3.6.19 Total plant nitrogen content

The N content of each plant was determined as the product of % N in the plant and plant dry matter weight as suggested by Unkovich *et al*. (2008).

$$Plant\ N\ content\ (kg\ ha^{-1}) = Dry\ matter\ (kg\ ha^{-1})\ \times\ \%\ N\ concentration\ of\ the\ plant$$

3.6.20 Nitrogen harvest index (NHI)

The NHI which is the proportion of N in the grain to the total plant N content in percentage (Salvagiotti *et al*., 2008) was estimated by dividing the N content of the grain by the total plant N content (grain N content + stover N content) multiplied by hundred.

$$N\ harvest\ index\ (NHI) = \frac{Grain\ N\ content\ (kg\ ha^{-1})}{Total\ plant\ N\ content\ (kg\ ha^{-1})}\ X\ 100$$

3.6.21 ^{15}N analysis and percentage N derived from the atmosphere (% ndfa)

For the ^{15}N analysis, samples for the grains and the stover were grounded, sieved using 80-mesh (0.2 mm) and prepared for nitrogen isotope analysis, by weighing a small amount (0.2-0.3mg) into 6 x 4 mm tin capsules and analysed for *^{15}N* and *% N* at OEA Laboratories Ltd, Callington, UK. The conversion of the solid sample to gaseous products and their subsequent analysis for isotopic composition was achieved through sample conversion using a Flash 1112 elemental analyser (Thermo Scientific, Bremen, Germany) coupled to a Delta V Advantage isotope ratio mass spectrometer (Thermo Scientific, Bremen, Germany). Measured isotope abundance values were scale calibrated to Air (^{15}N) based on 2-point end-member normalization using contemporaneously analysed international reference materials (RMs) obtained from the International Atomic Energy Agency (IAEA, Vienna, Austria). N fixed per hectare was estimated using ^{15}N natural abundance method as (Robinson *et al*., 2000; Unkovich *et al*., 2008; Mohale *et al*., 2014). The combined ^{15}N natural abundance of grain plus stover was calculated as an average of the ^{15}N natural abundance values of grain, stover and shell weight by their respective total N contents as (Robinson *et al*., 2000; Unkovich *et al*., 2008)

$$\delta\ ^{15}N\ _{whole\ plant} = \frac{\sum\left(\delta\ ^{15}N\ _{grain}\ \times\ N_{grain}\ +\ \delta\ ^{15}N\ _{stover}\ \times\ N_{stover}\right)}{\sum\left(N_{grain}\ +\ N_{stover}\right)}$$

The percent N derived from symbiotic fixation of atmospheric N_2 was estimated using the equation (Unkovich *et al*., 2008).

$$\%\ Ndfa = \frac{\delta\ ^{15}N_{ref} - \delta^{15}N_{leg}}{\delta^{15}N_{ref} - \beta} \times 100$$

where,

$\delta\ ^{15}N\ _{ref}$ is the ^{15}N natural abundance of reference plants,

$\delta\ ^{15}N\ _{leg}$ is the ^{15}N natural abundance of test legume,

β value is the ^{15}N natural abundance of test legume wholly dependent on N fixation for its N nutrition. The β value used in the present study was (-1.4‰) obtained from (Mohale *et al*., 2014) as recommended by (Unkovich *et al*., 2008).

3.6.22 fixed in the shoot

The N fixed in the shoot (grain + stover) was estimated using the procedure described by Mohale *et al*. (2014):

$$N\ fixed\ in\ the\ shoot = Plant\ N\ content\ (shoot)\ \times\ \%\ Ndfa\ (shoot)$$

3.6.23 Total N fixed

The total N fixed was determined using the procedure suggested by Unkovich *et al*. (2008) for pulse legumes as:

$$Total\ N\ fixed = N\ fixed\ in\ the\ shoot\ (grain + stover)\ \times\ 1.4$$

3.6.24 Soil N uptake

The soil N uptake of the crop was obtained by subtracting the N fixed in the shoot from the total N content of the crop.

$$Soil\ N\ uptake = Total\ N\ content\ of\ the\ crop - N\ fixed\ in\ the\ shoot$$

3.6.25 N balance studies

N balance which is a measure of the net N contribution of N fixing legumes to soil N (Haynes *et al*., 1993) was estimated using the procedure described in Singh *et al*. (2003):

$$N\ balance\ (+stover) = Total\ N\ fixed - N\ removed\ in\ the\ grain$$

$$N\ balance\ (-stover) = Total\ N\ fixed - N\ removed\ in\ the\ shoot\ (grain + stover)$$

3.6.24 Root studies

This was carried out at 4 and 8 weeks after sowing in the Screenhouse studies only. At each sampling period, the tops were severed from the roots using knife and immediately taken to the oven for drying. The oven temperature was maintained at 70^{o}C for 72 hrs. The roots were carefully washed, floated on water and scanned using Flatbed Scanner, Epson Expression 11000XL, Seiko, Japan with WinRhizo Pro version 2013 (Regent Instruments, Canada) software. Thereafter, the roots were dried in the oven with the temperatures maintained at 70^{o}C for 72 hrs. Root dry weight and root/shoot ratio were also determined.

3.7 Data analysis

The data collected were subjected analysis of variance procedure (ANOVA) using GenStat $^{(R)}$ 16th edition. Prior to each analysis, the assumption of normally distributed residuals was assessed using Shapiro-Wilk test while the assumption of homogeneity of variance was assessed using Bartletts's test in Genstat®. The specific procedure for each experiment is as described below.

3.7.1 Experiment 1

The data collected were subjected to one-way analysis of variance (ANOVA) procedure for randomized complete block design (RCBD) using Genstat® and means separation was carried out using Duncan's multiple range test in Genstat®.

3.7.2 Experiment 2

The data collected were subjected to two-way analysis of variance procedure (ANOVA) procedure for completely randomized design (CRD) using GenStat ® 16^{th} edition. Mean separation was carried out using Duncan's multiple range test in Genstat®.

3.7.3 Experiment 3

The data collected for the separate trials (first and second) were subjected to analysis of variance (ANOVA) procedure for randomized complete block design (RCBD) using GenStat ® 16^{th} edition. However, for the combined analysis, the individual trials were treated as split plots using General Linear Model (GLM) procedure in GenStat. Mean separation was carried out using Duncan's multiple range test in Genstat®.

CHAPTER FOUR

4. RESULTS

4.1 Experiment 1: Growth, yield, and N fixation of three Bambara groundnut landraces

4.1.1 Plant height, number of leaves, chlorophyll content and leaf area index (LAI)

The effects of landrace on plant height, number of leaves, chlorophyll content and leaf area index at 12 weeks after sowing are presented in Table 4.1.1. The Plant height of the crop ranged from 18.3-19.7 cm and was not significantly (P>0.05) different between the landraces. The number of leaves per plant ranged from 44-49 and was similar among the landraces. The chlorophyll content is the measure of plant N content and health and it ranged from 31.6-40.3 SPAD value. This was however not significantly different between the landraces. Leaf area index (a measure of plant canopy cover) ranged from 1.5-1.7 and was similar for all the landraces tested.

Table 4. 1. 1: Plant height, number of leaves, chlorophyll content (SPAD value) and leaf area index (LAI) of three Bambara groundnut landraces at 12 weeks after sowing (grain filling stage) during October-2013 to February-2014 growing season

Landrace	Plant height (cm)	Number of leaves per plant	Chlorophyll content (SPAD)	Leaf area index (LAI)
Ex-Sokoto	18.7	49	40.1	1.6
Kaaro	18.3	44	31.6	1.7
NN-1	19.7	45	40.3	1.5
SEM	0.65	2.46	3.44	0.09
P values	0.408	0.444	0.240	0.208

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values; SEM = Standard error of mean

4.1.2 Number of pods plant^{-1}, pod weight, shell weight, grain weight, haulm weight and total dry weight

The effects of landraces on the number of pods plant^{-1}, pod weight, shell weight, grain weight, haulm weight and total dry weight are presented in Table 4.1.2. The average number of pods per plant and pod weight were significantly ($P<0.05$) higher in Ex-Sokoto (41 pods plant^{-1}, 3152 kg ha^{-1}, respectively) landrace than Kaaro (11 pods plant^{-1}, 1207 kg ha^{-1}) and NN-1 (9 pods plant^{-1}, 1077 kg ha^{-1}). Both the number of pods per plant and pod weight in Kaaro and NN-1 landraces were similar ($P>0.05$).

The grain and haulm weight of the crop were significantly ($P<0.05$) higher in Ex-Sokoto (2256, 2030 kg ha^{-1}) than Kaaro (812, 1543 kg ha^{-1}) and NN-1 (703, 1645 kg ha^{-1}) for grain and haulm weight, respectively. Both Kaaro and NN-1 landraces recorded similar grain and haulm weight (Table 4.1.2).

The shell and total dry weight of the crop were significantly ($P<0.05$) higher in Ex-Sokoto (896, 5182 kg ha^{-1}) than Kaaro (395, 2750 kg ha^{-1}) and NN-1 (374, 2722 kg ha^{-1}) for shell weight and total dry weight, respectively.

Table 4. 1. 2: Number of pod plant^{-1}, pod weight, shell weight, grain weight, haulm weight and total dry weight of three Bambara groundnut landraces at harvest during October-2013 to February-2014 growing season

Landrace	Number of pods plant^{-1}	Pod weight	Shell Weight	Grain Weight	Haulm weight	Total dry weight
		------------------------------------- kg ha^{-1} --------------------				
Ex-Sokoto	41 a	3152 a	896 a	2256 a	2030 a	5182 a
Kaaro	11 b	1207 b	395 b	812 b	1543 b	2750 b
NN-1	9 b	1077 b	374 b	703 b	1645 b	2722 b
SEM	2.8	177.1	65.6	124.5	96.1	180.2
P values	0.002	0.002	0.008	0.002	0.048	<.001

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values; SEM = Standard error of mean

4.1.3 Shelling percentage (SP) and harvest index (HI)

Effects of landrace on shelling percentage and harvest index of Bambara groundnut are presented in Figure 4.1.1. The HI was observed to be significantly different among the landraces. Ex-Sokoto landrace recorded higher (43.4 %) harvest index than Kaaro (29.6 %) and NN-1 (26.1 %). However, the shelling percentage of the crop which ranged from 65.8-71.4 % was not significantly different ($P<0.05$) among the landraces.

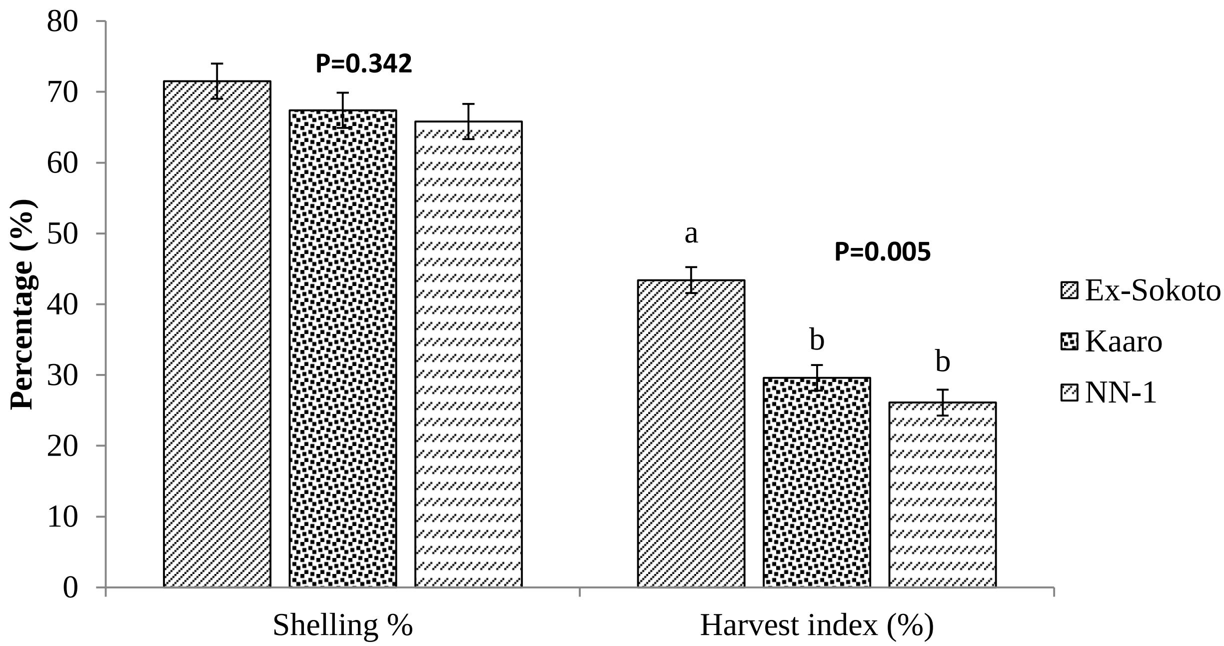

Figure 4. 1. 1: Shelling percentage and harvest index of three Bambara groundnut landraces during October-2013 to February-2014 growing season. Bars with the same letter are not significantly different at 5 % level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.1.4 Nitrogen concentration, nitrogen content and N-harvest index (NHI)

Nitrogen concentration, content and N-harvest index of the landraces are presented in Table 4.1.3. The N concentration ranged from 3.4-3.7 % in the grain, 1.3-2.1 % in the shell and 2.3-2.4 % in the haulm and was not significantly ($P>0.05$) different among the landraces. The grain and shell N content was significantly different among the landraces. Ex-Sokoto recorded higher grain and shell nitrogen content than Kaaro and NN-1. However, the N content in the haulm was not significantly different among the landraces. The NHI of the crop was significantly ($P<0.05$) different among the landraces. Ex-Sokoto translocated 56.6 % of its total N to the grain which was significantly higher than 38.3 and 35.5 % recorded by Kaaro and NN-1, respectively.

Table 4. 1. 3: Nitrogen concentration, nitrogen content and N-harvest index of three Bambara groundnut landraces during October-2013 to February-2014 growing season

Landrace	Nitrogen Concentration (%)			Nitrogen Content (kg ha^{-1})			N-harvest index (NHI) (%)
	Shell	Haulm	Grain	Shell	Haulm	Grain	
Ex-Sokoto	1.7	2.3	3.7	15.4 a	47.7	82.2 a	56.6 a
Kaaro	2.1	2.4	3.5	8.3 ab	37.0	28.0 b	38.3 b
NN-1	1.3	2.4	3.4	4.8 b	39.0	23.9 b	35.5 b
SEM	0.28	0.12	0.14	2.03	3.37	2.88	2.73
P values	0.259	0.910	0.440	0.049	0.170	<.001	0.010

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values; SEM = Standard error of mean

4.1.5 Total nitrogen content, percentage nitrogen derived from the atmosphere (% Ndfa), nitrogen fixed ha^{-1} and N balance

Total nitrogen content, percentage N derived from the atmosphere, N fixed per hectare and N balance of the landraces are presented in Table 4.1.4. Significant ($P<0.05$) effect of landrace on N content, N fixation and N balance (-haulm) was observed in the trial. Ex-Sokoto (83.2 kg ha^{-1}) recorded higher fixed N than Kaaro (31.9 kg ha^{-1}) and NN-1 (49.5 kg ha^{-1}) landraces. Similarly, total plant N accumulation was higher in Ex-Sokoto (145.3 kg Nha^{-1}) than Kaaro (73.3 kg Nha^{-1}) and NN-1 (67.7 kg Nha^{-1}). However, the proportion of N derived from the atmosphere (43.4-73.7 %) was not significantly different among the landraces.

The N balance study revealed that when only the grain is removed and the residues are returned to the soil [N balance (+ haulm)], the crop contributes up to 1-26 kg Nha^{-1} to the soil which was not significantly influenced by the landraces. However, where both the grain and haulm where removed [N balance (-haulm)] the crop depletes the soil of nitrogen ranging from 13.4-46.7 kg ha^{-1} with NN-1 removing the least amount (13.4 kg ha^{-1}).

Table 4. 1. 4: Total N content, % nitrogen derived from the atmosphere (% Ndfa), nitrogen fixed and N balance of three Bambara groundnut landraces during October, 2013-February, 2014 growing season

Landrace	Total N content [a] (kg ha^{-1})	Ndfa[b] (%)	Nitrogen fixed (kg ha^{-1})	N balance (+haulm)[c] (kg ha^{-1})	N balance (-haulm)[d] (kg ha^{-1})
Ex-Sokoto	145.3 a	57.2	83.2 a	1.0	-46.7 b
Kaaro	73.3 b	43.4	31.9 b	3.9	-33.1 ab
NN-1	67.7 b	73.7	49.5 b	25.6	-13.4 a
SEM	2.30	6.13	5.61	7.74	5.40
P values	<.001	0.060	0.007	0.159	0.030

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values; SEM = Standard error of mean

[a]Total N content = N in the shell + N in the haulm + N in the grain

[b]Ndfa = Nitrogen derived from the atmosphere

[c]N balance (+stover) = N fixed - N removed in the grain
[d]N balance (-stover) = N fixed - N removed in the shoot (grain + stover)

4.2 Experiment 2: Influence of rock phosphate levels on the growth, yield and N fixation of Bambara groundnut landraces.

4.2.1 Plant height, number of leaves and leaf area index (LAI)

Plant height, number of leaves and leaf area index of Bambara groundnut landraces at 4 and 8 weeks after sowing as influenced by rock phosphate levels are presented in Table 4.2.1.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in the LAI of the crop was observed at 4 and 8 weeks after sowing (WAS) during the trial. Kaaro landrace recorded LAI values of 0.79 and 1.81 at 4 and 8 WAS, respectively which was higher than 0.45 and 1.24, respectively recorded by Ex-Sokoto landrace. However, despite the differences in the LAI values between the landraces, the plant height which ranged from 16.9-18.1 cm and 22.5-23.8 cm at 4 and 8 WAS, respectively and the number of leaves per plant which ranged from 18-20 and 46-48 leaves, respectively were not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect of rock phosphate (RP) application on the plant height, number of leaves and LAI of Bambara groundnut was observed in the trial. Application of RP (20-60 kg P_2O_5 ha^{-1}) increased the plant height of the crop from 13.7 cm and 18.5 cm recorded at 4 and 8 WAS, respectively in the control plots (0 kg P_2O_5 ha^{-1}) to 18.5-19.2 cm and 24.2-25.7 cm, respectively. The difference between the RP levels of 20-60 kg P_2O_5 ha^{-1} on the plant height of the crop was not observed. The number of leaves per plant at 4 WAS ranged from 13-23 leaves and was highest (23 leaves per plant) where 20 kg P_2O_5 ha^{-1} was applied and the least (13 leaves per plant) was recorded in the control plots. However, at 8 WAS, the number of leaves per plant which ranged from 28-65 was highest (65 leaves per plant) at the application of 40 kg P_2O_5 ha^{-1}, whereas the least (28 leaves per plant) was recorded in the control plots. The LAI of the crop ranged from 0.35-0.77 and 0.70-2.34 at 4 and 8 WAS, respectively. At 4 WAS, the highest leaf area index of 0.77 was recorded at the application of 20 kg P_2O_5 ha^{-1}, whereas at 8 WAS, the highest LAI (2.34) was recorded at the application of 40 kg P_2O_5 ha^{-1}. The control plots (0 kg P_2O_5 ha^{-1}) recorded the least LAI values of 0.35 and 0.70 at 4 and 8 WAS, respectively.

Table 4. 2. 1: Plant height, number of leaves and leaf area index of Bambara groundnut landraces at 4 and 8 weeks after sowing (WAS) as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Plant height (cm)		Number of leaves		Lear area index (LAI)	
	4 WAS	8WAS	4 WAS	8WAS	4 WAS	8WAS
Landrace (L)						
Ex-Sokoto	16.9	22.5	18	48	0.45b	1.24b
Kaaro	18.1	23.8	20	46	0.80a	1.81a
SEM	0.580	0.795	1.032	1.810	0.047	0.119
P values	0.174	0.253	0.106	0.298	<.001	0.004
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg $soil^{-1}$)						
0 (0.00)	13.7b	18.5b	13c	28d	0.35b	0.70c
20 (0.28)	18.5a	24.3a	23a	44c	0.77a	1.45b
40 (0.56)	18.7a	25.7a	21ab	65a	0.75a	2.34a
60 (0.84)	19.2a	24.2a	19b	52b	0.61a	1.62b
SEM	0.820	1.124	1.460	2.550	0.067	0.168
P values	<.001	0.002	0.001	<.001	0.002	<.001
Interaction (L X RP)						
P values	0.794	0.698	0.627	0.119	0.095	0.238

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.2 Chlorophyll content (SPAD Value), shoot and total plant dry weight

Chlorophyll content, shoot and total plant dry weight of Bambara groundnut landraces at 4 and 8 weeks after sowing as influenced by rock phosphate levels are presented in Table 4.2.2.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in shoot weight and total plant dry weight was observed at 4 WAS. Kaaro landrace recorded higher shoot and total plant dry weight of 2.8 g and 3.8 g plant^{-1}, respectively than Ex-Sokoto landrace which recorded 2.1 g and 2.7 g plant^{-1}, respectively. However, despite the differences between the landraces in shoot and total plant dry weight observed at 4 WAS, the shoot weight (10.2-11.6 g plant^{-1}) and total plant dry weight (13.4-15.3 g plant^{-1}) of the crop at 8 WAS were not significantly ($P>0.05$) different between the landraces. The leaf chlorophyll content (SPAD Value) which ranged from 49.2-50.3 and 50.4-51.1 at 4 and 8 WAS, respectively was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect RP application on shoot and total plant dry weight of the crop was observed at 4 and 8 WAS during the trial. At 4 WAS, application of RP at the rate of 20-60 kg P_2O_5 ha^{-1} increased the shoot and total plant dry weight from 1.6 g and 2.49 g plant^{-1}, respectively recorded where no RP was applied to 2.4-2.8 g and 3.0-3.8 g plant^{-1} for shoot and total plant dry weight, respectively. No significant ($P>0.05$) difference between the RP levels of 20-60 kg P_2O_5 ha^{-1} on the shoot and total plant dry weight was observed. However, at 8 WAS, the highest shoot and total plant dry weight of 17.1g and 21.5 g plant^{-1}, respectively were recorded where 40 kg P_2O_5 ha^{-1} was applied, followed by the application of 20 and 60 kg P_2O_5 ha^{-1} (11.0-

11.9 and 15.0-15.6 g plant^{-1}, respectively) and the least (3.7 and 5.3 g plant^{-1}, respectively) was recorded were no RP was applied. The leaf chlorophyll content which ranged from 47.0-51.6 and 47.5-52.7 at 4 and 8 WAS, respectively was not influenced by the application of RP on the crop.

Table 4. 2. 2: Leaf chlorophyll content (SPAD Value), shoot weight and total plant dry weight of Bambara groundnut landraces at 4 and 8 weeks after sowing (WAS) as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Leaf chlorophyll content (SPAD Value)		Shoot weight (g $plant^{-1}$)		Total Plant dry weight (g $plant^{-1}$)	
	4 WAS	8WAS	4 WAS	8WAS	4 WAS	8WAS
Landrace (L)						
Ex-Sokoto	50.3	51.1	2.1b	10.2	2.7b	13.4
Kaaro	49.2	50.4	2.8a	11.6	3.8a	15.3
SEM	1.83	1.25	0.149	0.952	0.179	1.131
P values	0.670	0.697	0.002	0.318	<.001	0.273
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg $soil^{-1}$)						
0 (0.00)	51.6	47.5	1.6b	3.7c	2.5b	5.3c
20 (0.28)	48.9	48.8	2.8a	11.0b	3.7a	15.0b
40 (0.56)	51.5	52.1	2.8a	17.1a	3.8a	21.5a
60 (0.84)	47.0	52.7	2.4a	11.9b	3.0ab	15.6b
SEM	2.59	2.71	0.211	1.346	0.254	1.599
P values	0.547	0.118	0.003	<.001	0.009	<.001
Interaction (L X RP)						
P values	0.549	0.824	0.225	0.246	0.636	0.265

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.3 Root length, volume and diameter

Root length, volume and diameter of Bambara groundnut landraces at 4 and 8 weeks after sowing as influenced by rock phosphate levels are presented in Table 4.2.3.

Effect of landrace

Significant ($P<0.05$) differences between the landraces in root length and volume were observed at 4 weeks after sowing (WAS) during the trial. Kaaro landrace recorded higher root length (1709 cm) and volume (1.79 cm^3) than Ex-Sokoto landrace which recorded 1346 cm and 1.19 cm^3, respectively. However, the root diameter (0.33-0.37 mm) of the crop at 4 WAS, and the root length (5090-5585 cm), volume (6.99-7.29 cm^3) and diameter (0.39-0.42 mm) at 8 WAS were not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect of rock phosphate application on the root length and volume of the crop was observed at 8 WAS. Application of 20-60 kg P_2O_5 ha^{-1} significantly ($P<0.05$) increased the root length and volume of the crop at 8 WAS from 3506 cm and 3.76 cm^3, respectively recorded where no RP was applied to 5657-6098 cm and 7.77-9.09 cm^3, respectively which was not significantly ($P>0.05$) different among the RP levels (20-60 kg P_2O_5 ha^{-1}). However, the root diameter of the crop at 8 WAS which ranged from 0.366-0.453 mm was not significantly ($P>0.05$) influenced by the application of RP on the crop. similarly, at 4 WAS the root length (1372-1631 cm), volume (1.15-1.69 cm^3) and diameter (0.33-0.38 mm) were not significantly ($P>0.05$) influenced by the application of RP on the crop.

Table 4. 2. 3: Root length, volume and diameter of Bambara groundnut landraces at 4 and 8 weeks after sowing (WAS) as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Root length (cm)		Root volume (cm^3)		Root diameter (mm)	
	4 WAS	8WAS	4 WAS	8WAS	4 WAS	8WAS
Landrace (L)						
Ex-Sokoto	1346b	5090	1.19b	7.29	0.33	0.42
Kaaro	1709a	5585	1.79a	6.99	0.37	0.39
SEM	102.8	295.0	0.107	0.594	0.013	0.017
P values	0.024	0.253	0.001	0.724	0.109	0.194
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg $soil^{-1}$)						
0 (0.00)	1631	3506b	1.46	3.76b	0.33	0.37
20 (0.28)	1528	6088a	1.69	7.77a	0.38	0.41
40 (0.56)	1578	5657a	1.67	9.09a	0.37	0.45
60 (0.84)	1372	6098a	1.15	7.93a	0.33	0.41
SEM	145.4	417.2	0.151	0.839	0.019	0.024
P values	0.631	0.001	0.081	0.002	0.185	0.137
Interaction (L X RP)						
P values	0.718	0.574	0.112	0.499	0.517	0.744

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.4 Root weight, surface area and root/shoot ratio

Root weight, surface area and root/shoot ratio of Bambara groundnut landraces at 4 and 8 weeks after sowing as influenced by rock phosphate levels are presented in Table 4.2.4.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in root weight and surface area was observed at 4 WAS during the trial. At 4 WAS, Kaaro landrace was significantly ($P<0.05$) higher in root weight (0.96 g) and surface area (195 cm^2) than Ex-Sokoto landrace (0.65 g and 141 cm^2, respectively). However, at 8 WAS the root weight (3.21-3.64 g) and surface area (675-694 cm^2) of the crop were not significantly ($P<0.05$) different between the landraces. Similarly, the root/shoot ratio of the landraces at 4 (0.35-0.36) and 8 WAS (0.34-0.36) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect of RP application on the root weight and root/shoot ratio of the crop was observed at 4 and 8 WAS, whereas for the root surface area the effect of RP application was only observed at 8 WAS. At 4 WAS, application of 20-40 kg P_2O_5 ha^{-1} recorded root weight of 0.82-0.92 g $plant^{-1}$ which was not significantly ($P>0.05$) different from 0.87 g $plant^{-1}$ observed in the control plots (0 kg P_2O_5 ha^{-1}). However, at 60 kg P_2O_5 ha^{-1} the root weight of the crop was significantly ($P<0.05$) decreased to 0.61 g $plant^{-1}$. Application of RP (20-60 kg P_2O_5 ha^{-1}) decreased the root/shoot ratio of the crop at 4 WAS from 0.54 recorded in the control plots (0 kg P_2O_5 ha^{-1}) to 0.26-0.32. However, the root surface area of the crop at 4 WAS (141-180 cm^2) was not significantly ($P>0.05$) influenced by the application of RP on the crop. At 8 WAS, application of RP (20-60 kg ha^{-1}) increased the root weight and surface area of the crop from 1.57 g and 406 cm^2, respectively recorded where no RP was applied to 3.78-4.42 g and 763-804 cm^2, respectively. However, for the root/shoot ratio at 8 WAS, the highest value of 0.42 was recorded where no RP was applied which was not significantly ($P>0.05$) different from 0.33-0.37 recorded at the application of 20 and 60 kg P_2O_5 ha^{-1}. Application of 40 kg P_2O_5 ha^{-1} recorded lower root/shoot ratio of 0.27 and which was also not significantly different ($P>0.05$) from 0.33-0.37 recorded at the application of 20 and 60 kg P_2O_5 ha^{-1}.

Table 4. 2. 4: Root weight, surface area and root/shoot ratio of Bambara groundnut landraces at 4 and 8 weeks after sowing (WAS) as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Root weight (g plant $^{-1}$)		Root surface area (cm^2)		Root/shoot ratio	
	4 WAS	8WAS	4 WAS	8WAS	4 WAS	8WAS
Landrace (L)						
Ex-Sokoto	0.65b	3.21	141b	675	0.35	0.34
Kaaro	0.96a	3.64	195a	694	0.37	0.36
SEM	0.048	0.271	9.53	39.0	0.023	0.024
P values	<.001	0.283	0.001	0.735	0.574	0.658
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg soil^{-1})						
0 (0.00)	0.87a	1.57b	171	406b	0.54a	0.42a
20 (0.28)	0.82a	3.93a	179	763a	0.32b	0.37ab
40 (0.56)	0.92a	4.42a	180	804a	0.32b	0.27b
60 (0.84)	0.61b	3.78a	141	767a	0.26b	0.33ab
SEM	0.068	0.384	13.5	55.1	0.033	0.034
P values	0.026	<.001	0.175	<.001	<.001	0.036
Interaction (L X RP)						
P values	0.133	0.592	0.186	0.490	0.058	0.671

Means followed by same letter(s) within a column are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.5 Number of pods plant^{-1} and 1000-grain weight

Number of pods plant^{-1} and 1000-grain weight of Bambara groundnut landraces as influenced by rock phosphate levels are presented in Table 4.2.5.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in 1000-grain weight was observed during the trial. Kaaro landrace recorded higher 1000-grain weight (534 g) than Ex-Sokoto (409 g). However, despite the differences in the 1000-grain weight recorded by the landraces, the number of pods plant^{-1} (34-35 pods) was not significantly different ($P>0.05$) between the landraces (Figure 4.2.1).

Effect of rock phosphate

Significant ($P<0.05$) effect of RP application on the number of pods plant^{-1} was observed during the trial. Application of 20 kg P_2O_5 ha^{-1} increased the number of pods plant^{-1} from 13 pods recorded at 0 kg P_2O_5 ha^{-1} to 33 pods plant^{-1}. However, increasing the RP level from 20 to 40 kg P_2O_5 ha^{-1} did not result in significant increase in the number of pods plant^{-1}. Similarly, increase in RP from 40 to 60 kg P_2O_5 ha^{-1} did not increase the number of pods plant^{-1}. 60 kg P_2O_5 ha^{-1} recorded higher (49 pods) number of pods plant^{-1} than 20 kg P_2O_5 ha^{-1} (33 pods plant^{-1}). 40 kg P_2O_5 ha^{-1} was thus optimum for number of pods plant^{-1} (44 pods). However, despite the increase in the number of pods plant^{-1} as a result of RP application, the 1000-grain weight of the landraces (396-509 g) was not influenced by rock phosphate application.

Table 4. 2. 5: Number of pods plant^{-1} and 1000-grain weight of Bambara groundnut landraces as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Number of pods plant^{-1}	1000-grain weight (g)
Landrace (L)		
Ex-Sokoto	35	409b
Kaaro	34	534a
SEM	1.96	24.5
P values	0.906	0.002
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg soil^{-1})		
0 (0.00)	13c	396
20 (0.28)	33b	487
40 (0.56)	44ab	509
60 (0.84)	49a	493
SEM	2.77	34.6
P values	<.001	0.133
Interaction (L x RP)		
P values	0.985	0.333

Means in a column followed by same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.6 Pod weight, grain weight, shelling percentage, haulm weight, total dry weight and harvest index

Pod weight, grain weight, shelling percentage, haulm weight, total dry weight and harvest index of Bambara groundnut landraces as influenced by rock phosphate levels are presented in Table 4.2.6.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in terms of mean pod, grain, haulm and total dry weight was observed in the study. The pod weight (18.6-23.8 g), grain weight (13.2-18.0 g), haulm weight (22.3-32.9 g) and total dry weight (40.9-56.7) were higher in Kaaro landrace (pod weight, 23.8 g; grain weight,18.0 g; haulm weight, 32.9 g and total dry weight, 56.7 g) than Ex-Sokoto landrace (pod weight,18.6 g; grain weight, 13.2 g; haulm weight, 22.3 g and total dry weight, 40.9 g). However, despite the differences between the two landraces in pod, grain, haulm and total dry weight, the shelling percentage (70.9-71.9 %) and harvest index (28.3-29.0 %) were not significantly ($P>0.05$) different.

Effect of rock phosphate

Results showed significant ($P<0.05$) effect of RP application on the pod, grain, haulm and total dry weight of the crop. Application of 40-60 kg P_2O_5 ha^{-1} was highest in pod (27.8-30.7 g) and grain (21.1-22.0 g) weight followed by the application of 20 kg P_2O_5 ha^{-1} (19.8 and 15.0 g for pod and grain weight, respectively) and the least pod (6.4 g) and grain (4.4 g) weight were recorded where no RP was applied. The haulm (12.4-35.1 g) and total dry weight (18.8-69.2 g) recorded in this study were higher (30.3-35.1 g and 52.5-62.9 g for haulm and total dry weight, respectively) in the treatments receiving RP (20-60 kg P_2O_5 ha^{-1}) application than in the control (0 kg P_2O_5 ha^{-1}). The difference among the RP levels of 20-60 kg P_2O_5 ha^{-1} was not observed in both the haulm and total dry weight. However, despite the differences in the pod, grain, haulm and total dry weight recorded as a result of RP application on the crop, the shelling percentage (68.2-75.1 %) and harvest index (19.2-34.2) were not significantly ($P>0.05$) influenced by the application of RP on the crop.

Interactions

Significant ($P<0.05$) interaction between the landraces and rock phosphate application was observed on the haulm weight of the crop (Figure 4.2.1). At 0 kg P_2O_5 ha^{-1}, the haulm weight (11.2-11.7 g $plant^{-1}$) of the landraces was not significantly ($P>0.05$) different. Application of 20 kg P_2O_5 ha^{-1} on Kaaro landrace resulted in significant ($P<0.05$) increase in the haulm weight of the landrace to 36.6 g $plant^{-1}$ compared to 11.7 kg recorded at 0 kg P_2O_5 ha^{-1}. Further increase from 20 to 60 kg P_2O_5 ha^{-1} did not result in significant increase in the haulm weight of Kaaro. In contrast, there was no significant effect of RP on the haulm weight of Ex-Sokoto.

Table 4. 2. 6: Pod weight, grain weight, shelling percentage, haulm weight, total dry weight and harvest index of Bambara groundnut landraces as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Pod weight (g)	Grain weight (g)	Shelling percentage (%)	Haulm weight (g)	Total dry weight (g)	Harvest index (%)
Landrace (L)						
Ex-Sokoto	18.6b	13.2b	70.9	22.3b	40.9b	29.0
Kaaro	23.8a	18.0a	71.9	32.9a	56.7a	28.3
SEM	1.066	1.001	1.49	1.78	2.42	2.72
P values	0.003	0.004	0.664	<.001	<.001	0.852
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg $soil^{-1}$)						
0 (0.00)	6.4c	4.4c	68.2	12.4b	18.8b	19.2
20 (0.28)	19.8b	15.0b	75.1	32.7a	52.5a	27.8
40 (0.56)	27.8a	21.1a	71.0	35.1a	62.9a	33.5
60 (0.84)	30.7a	22.0a	71.2	30.3a	61.0a	34.2
SEM	1.507	1.415	2.11	2.51	3.42	3.85
P values	<.001	<.001	0.185	<.001	<.001	0.051
Interaction (L x RP)						
P values	0.126	0.199	0.578	0.027	0.064	0.307

Means in a column followed by same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

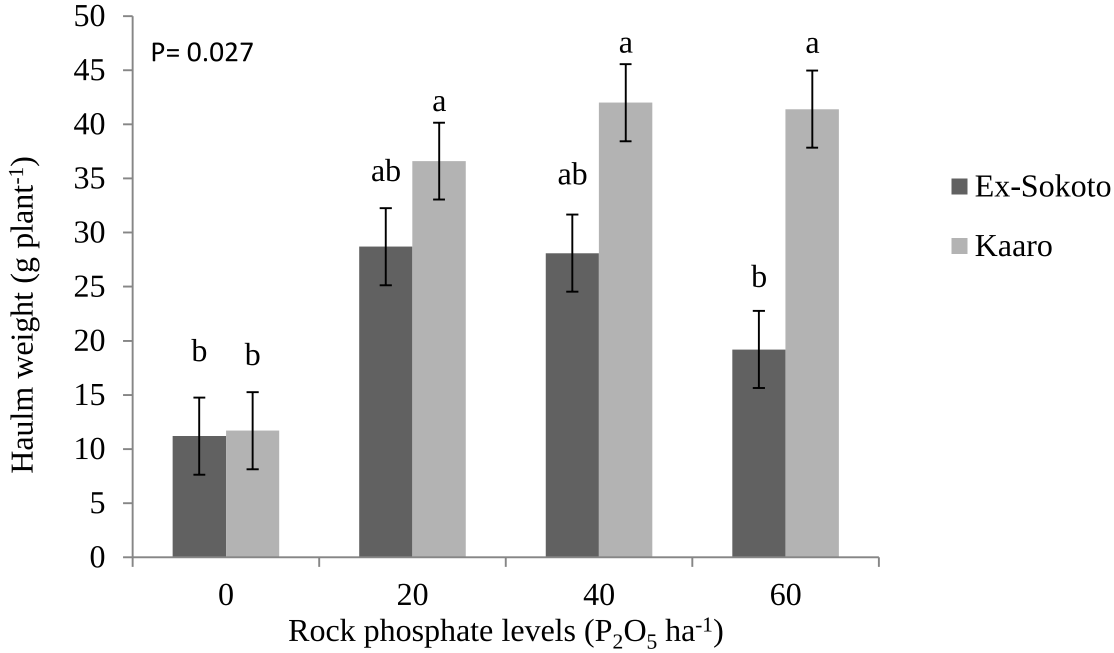

Figure 4. 2. 1: Effect of interaction between the landraces and rock phosphate levels on haulm weight of Bambara groundnut. Error bars are SEM values. Bars with the same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test.

4.2.7 Nitrogen concentration, N content and N harvest index (NHI)

Nitrogen concentration, N content and N harvest index of Bambara groundnut landraces as influenced by rock phosphate levels are presented in Table 4.2.7.

Effect of landrace

The N content of the landraces in the grain (437-633 mg plant^{-1}), stover (798-1135 mg plant^{-1}) and the total plant (1235-1767 mg plant^{-1}) was significantly ($P<0.05$) higher in Kaaro landrace (633, 1135 and 1767 mg plant^{-1} for grain, stover and the total plant, respectively) than Ex-Sokoto landrace (437, 798 and 1235 mg plant^{-1}). However, despite the differences in the N content, the N concentration in the grain (3.16-3.38 %), stover (2.84-2.93 %) and N harvest index (33.7-34.1 %) were not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect of RP application on the grain N concentration (2.86-3.52 %) of Bambara groundnut was observed in the study. Results showed progressive increase in the grain N concentration as a result of RP application from 0 to 60 kg P_2O_5 ha^{-1}. Application of 20 kg P_2O_5 ha^{-1} increased the grain N concentration from 2.86 % recorded where no RP was applied to 3.20 %. Further increase in RP from 20 kg P_2O_5 ha^{-1} to 40 kg P_2O_5 ha^{-1} did not result in significant increase in the grain N concentration (3.52 %) and was similar to that observed in the treatments applied 60 kg P_2O_5 ha^{-1} (3.50 %). However, despite the differences in the grain N concentration recorded as a result of RP application, the stover N concentration (2.77-2.98 %) was not influenced by RP application on the crop.

Significant ($P<0.05$) effect of RP application on the grain (125-769 mg plant^{-1}), stover (433-1159 mg plant^{-1}) and total (557-1925 mg plant^{-1}) N content was observed in the experiment. Application of 20 kg P_2O_5 ha^{-1} was higher (490 mg plant^{-1}) in grain N content than 0 kg P_2O_5 ha^{-1} (125 mg $plant^{-1}$). Increasing RP application to 40 kg P_2O_5 ha^{-1} further increased the grain N content to 756 mg $plant^{-1}$ which was similar to 769 mg $plant^{-1}$ recorded in the treatments applied 60 kg P_2O_5 ha^{-1} but higher than the grain N content recorded at the application of 0-20 kg P_2O_5 ha^{-1}. For the haulm and total N content however, application of 20 kg P_2O_5 ha^{-1} recorded higher haulm (1117 mg) and total N (1607 mg $plant^{-1}$) than 433 and 557 mg $plant^{-1}$ recorded where no RP was applied. Further increase in the RP levels from 40-60 kg P_2O_5 ha^{-1} did not significantly increase the haulm (1156-1159 mg $plant^{-1}$) and total N (1915-1925 mg $plant^{-1}$) content of the crop.

Significant ($P<0.05$) effect of RP application on the NHI of the landraces was observed in the trial. Application of 20 kg P_2O_5 ha^{-1} recorded NHI of 30 % which was not significantly different from the 22.9 % recorded where no RP was applied. Further increase in RP application to 40 kg P_2O_5 ha^{-1} increased the NHI of the crop to 39.2 % which was similar to the 30 % recorded by the application of 20 kg P_2O_5 ha^{-1} but higher than 22.9 % recorded where no RP was applied. Similarly, application of 60 kg P_2O_5 ha^{-1} further increased the NHI of the crop to 43.4 % but was similar to 30.0 % and 39.2 % recorded by the application of 20 and 40 kg P_2O_5 ha^{-1} respectively. Thus, application of 20 kg P_2O_5 ha^{-1} appeared to optimize the NHI of the landraces.

Table 4. 2. 7: Nitrogen concentration, N content and nitrogen harvest index (NHI %) of Bambara groundnut landraces as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Nitrogen concentration		Nitrogen content			NHI (%)
	----------- (%)------		------------ (mg $plant^{-1}$) -------			
	Grain	Stover	Grain	Stover	Total	
Landrace (L)						
Ex-Sokoto	3.16	2.84	437b	798b	1235b	34.1
Kaaro	3.38	2.93	633a	1135a	1767a	33.7
SEM	0.090	0.111	44.9	79.4	91.6	2.42
P values	0.113	0.593	0.007	0.009	<.001	0.913
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg $soil^{-1}$)						
0 (0.00)	2.86b	2.98	125c	433b	557b	22.9b
20 (0.28)	3.20ab	2.95	490b	1117a	1607a	30.0ab
40 (0.56)	3.52a	2.77	756a	1159a	1915a	39.2a
60 (0.84)	3.50a	2.83	769a	1156a	1925a	43.4a
SEM	0.128	0.157	63.5	112.3	129.6	3.42
P values	0.007	0.747	<.001	<.001	<.001	0.003
Interaction (L x RP)						
P values	0.661	0.179	0.287	0.055	0.060	0.055

Means in a column followed by same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.2.8 Percentage N derived from the atmosphere (% ndfa), N fixed in the shoot, total N fixed, soil mineral N uptake and N balance

Percentage N derived from the atmosphere (% ndfa), N fixed in the shoot, total N fixed, soil mineral N uptake and N balance of Bambara groundnut landraces as influenced by rock phosphate levels are presented in Table 4.2.8.

Effect of landrace

The % ndfa of the landraces (34.0-36.2 %) recorded in this experiment was higher in Kaaro landrace (36.2 %) than in Ex-Sokoto landrace (34.0 %). Similarly, the N fixed in the shoot (419-639 mg plant^{-1}), total N fixed (587-894 mg plant^{-1}) and soil mineral N uptake (815-1129 mg plant^{-1}) were higher in Kaaro landrace (639, 894 and 1129 mg plant^{-1}, respectively) than in Ex-Sokoto landrace which recorded 419, 587 and 815 mg plant^{-1}, respectively. The N balance studies on the landraces revealed that when only the grains were removed and the residues returned to the soil (N balance +stover), the crop contributed 150-261 mg plant^{-1} which was not different between the landraces. However, when the residues were removed along with the grains (N balance -stover), the crop depleted the soil N with values ranging from 648-873 mg plant^{-1}. Ex-Sokoto landrace removed the lower value of 648 mg compared to Kaaro landrace which removed 873 mg plant^{-1}.

Effect of rock phosphate

Significant ($P<0.05$) effect of RP application on the % ndfa (33.9-37.6 %) of the landraces was observed in the trial. Application of 20-40 kg P_2O_5 ha^{-1} recorded % ndfa of 33.9 % and was similar to 35.1 % recorded where no RP (0 kg P_2O_5 ha^{-1}) was applied. Similarly, application of 60 kg P_2O_5 ha^{-1} recorded % ndfa of 37.6 % which was higher than 33.9 % recorded by the application of 20-40 kg P_2O_5 ha^{-1} but similar to 35.1 % recorded in the treatments receiving no RP application. Thus, the increase in the % ndfa of the landraces as result of RP application was not consistent.

Significant ($P<0.05$) effect of RP application on the N fixed in the shoot (196-719 mg plant^{-1}), total N fixed (274-1007 mg plant^{-1}) and soil mineral N uptake (362-1263 mg plant^{-1}) was observed in the trial. Application of 20 kg P_2O_5 ha^{-1} recorded higher N fixed in the shoot (549 mg plant^{-1}), total N fixed (769 mg plant^{-1}) and soil mineral N uptake (1057 mg plant^{-1}) than 0 kg P_2O_5 ha^{-1} which recorded 196, 274 and 362 mg plant^{-1}, respectively. Further increase in the RP level from 40 to 60 kg P_2O_5 ha^{-1} resulted in 652-719 mg plant^{-1}, 913-1007 mg plant^{-1} and 1206-1263 mg plant^{-1} for N fixed in the shoot, total N fixed and soil mineral N uptake, respectively which were not significantly different from 549, 769 and 1057 mg plant^{-1}, respectively recorded at the application of 20 kg P_2O_5 ha^{-1}. Thus application of 20 kg P_2O_5 ha^{-1} was optimum for N fixation of the landraces.

Significant ($P<0.05$) effect of RP application on the N balance (-stover) of the crop was observed in the trial. The N balance (-stover) showed that when the residues were removed along with the grains (N balance -stover), the crop depleted the soil N with values ranging from 284-1002 mg plant^{-1}. The treatments receiving no RP application depleted the lower soil N (284 mg plant^{-1}) as a result of residues removal along with the grain when compared to the treatments supplied with 20-60 kg P_2O_5 ha^{-1} which removed 838-1002 mg plant^{-1}. However, when only the grains were removed and the residues returned to the soil (N balance +stover), the crop contributes 149-279 mg plant^{-1} which was not different among the rock phosphate levels.

Table 4. 2. 8: Percentage N derived from atmospheric fixation (% ndfa), N fixed in the shoot, total N fixed, soil mineral N uptake, N balance (+haulm) and N balance (-haulm) of Bambara groundnut landraces as influenced by rock phosphate levels in the Screenhouse, The University of Nottingham Malaysia Campus

Treatment	Ndfa[a] (%)	N fixed in the shoot[b]	Total N fixed[c]	Soil mineral N uptake[d]	N balance (+stover)[e]	N balance (-stover)[f]
		------------------------ mg plant^{-1}	----------------------------			
Landrace (L)						
Ex-Sokoto	34.0b	419b	587b	815b	150	-648a
Kaaro	36.2a	639a	894a	1129a	261	-873b
SEM	0.499	34.3	48.1	60.0	48.8	48.4
P values	0.007	<.001	<.001	0.002	0.127	0.005
Rock Phosphate (RP) levels (P_2O_5 ha^{-1}) (g kg soil^{-1})						
0 (0.00)	35.1ab	196b	274b	362b	149	-284a
20 (0.28)	33.9b	549a	769a	1057a	279	-838b
40 (0.56)	33.9b	652a	913a	1263a	157	-1002b
60 (0.84)	37.6a	719a	1007a	1206a	238	-918b
SEM	0.706	48.5	68.0	84.8	69.0	68.4
P values	0.006	<.001	<.001	<.001	0.492	<.001
Interaction (L x RP)						
P values	0.006	0.109	0.109	0.044	0.335	0.036

Means in a column followed by same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

[a]Ndfa = Nitrogen derived from the atmosphere

[b]N fixed in the shoot = N fixed in the grain + N fixed in the stover (haulm + shells)

[c]Total N fixed= N fixed in the shoot × 1.4 (Unkovich *et al*., 2008)

[d]Soil mineral N uptake = Shoot N content - N fixed in the shoot

[e]N balance (+stover) = total N fixed - N removed in the grain

[f]N balance (-stover) = total N fixed - N removed in the shoot (grain + stover)

Interactions

Significant ($P<0.05$) interaction between the landraces and rock phosphate application on % ndfa of Bambara groundnut was observed during the trial (Figure 4.2.2). For Ex-Sokoto landrace, application of 60 kg P_2O_5 ha^{-1} recorded 38.9 % ndfa which was significantly ($P<0.05$) higher than 31.2-33.81 % recorded in the treatments applied 0-40 kg P_2O_5 ha^{-1} on the same landrace. In contrast, there was no significant ($P>0.05$) effect of RP application on the % ndfa of Kaaro landrace (35.6-36.5 %).

Significant ($P<0.05$) interaction between the landraces and rock phosphate application on soil mineral N uptake of Bambara groundnut was observed during the trial (Figure 4.2.3). For Kaaro landrace, application of 20 kg P_2O_5 ha^{-1} significantly ($P<0.05$) increased the soil mineral N uptake from 342 mg $plant^{-1}$ recorded at 0 kg P_2O_5 ha^{-1} to 1261 mg $plant^{-1}$. Further increase in RP application from 40-60 kg P_2O_5 ha^{-1} recorded soil mineral N uptake of 1359-1553 mg $plant^{-1}$ which was not significantly ($P>0.05$) different from 1261 mg recorded by the application on 20 kg P_2O_5 ha^{-1} on the same landrace. For Ex-Sokoto landrace however, application of 20 kg P_2O_5 ha^{-1} recorded soil mineral N uptake of 854 mg $plant^{-1}$ which was not significantly ($P>0.05$) different from 382 mg $plant^{-1}$ recorded where no RP was applied on the same landrace. Similarly, application of 40 kg P_2O_5 ha^{-1} recorded soil mineral N uptake of 1359 mg $plant^{-1}$ which was higher than 382 mg $plant^{-1}$ recorded at 0 kg P_2O_5 ha^{-1} but similar to 854-859 mg $plant^{-1}$ recorded at 20 and 60 kg P_2O_5 ha^{-1}. In the overall, application of 20 kg P_2O_5 ha^{-1} appeared to maximize the soil mineral N uptake in the two landraces.

Significant ($P<0.05$) interaction between the landraces and rock phosphate application on N balance (-stover) was observed in the experiment (Figure 4.2.4).

For Kaaro landrace, the removal of stover along with the grain in the treatments where no RP was applied led to soil N depletion of 263 mg plant^{-1} which was lower than the soil N depleted (983-1198 mg plant^{-1}) in the treatments applied with RP at 20-60 kg P_2O_5 ha^{-1}. For Ex-Sokoto landrace however, removal of the stover along with the grain in the treatments applied 20 kg P_2O_5 ha^{-1} led to soil N depletion of 693 mg plant^{-1} which was not significantly ($P>0.05$) different from 304 mg plant^{-1} recorded where no RP was applied. However, the soil N depletion (956 mg plant^{-1}) recorded in the treatments applied 40 kg P_2O_5 ha^{-1} on the same landrace was significantly higher than 304 mg plant^{-1} recorded in the treatments where no RP was applied but similar to 693 and 638 mg plant^{-1} respectively recorded where 20 and 60 kg P_2O_5 ha^{-1} were applied on the same landrace. Thus, removal of the crop residues along with the grain in the treatments were RP was applied was observed to be relatively higher than in the treatments were no RP was applied in both the landraces.

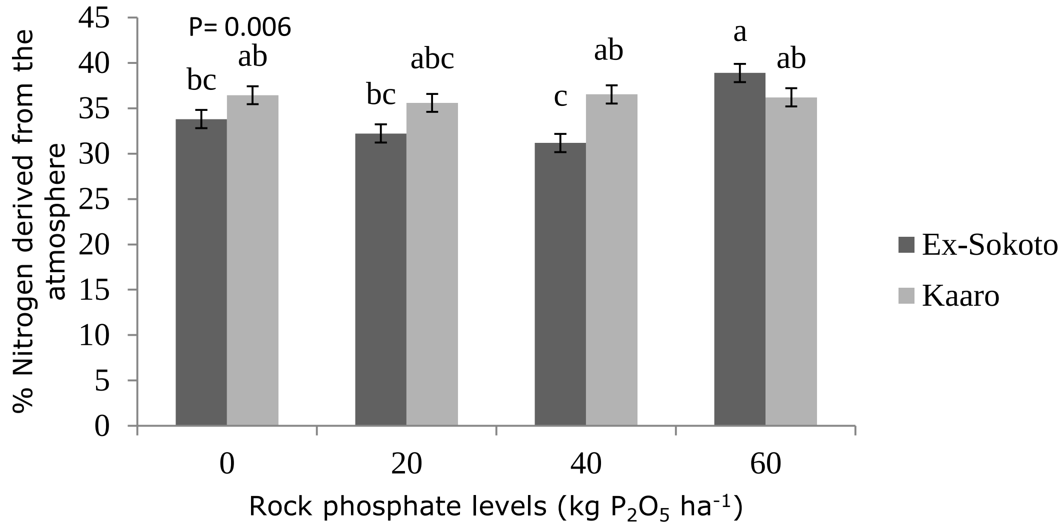

Figure 4. 2. 2: Effect of interaction between the landraces and rock phosphate levels on % nitrogen derived from the atmosphere in Bambara groundnut. Error bars are SEM values. Bars with the same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test.

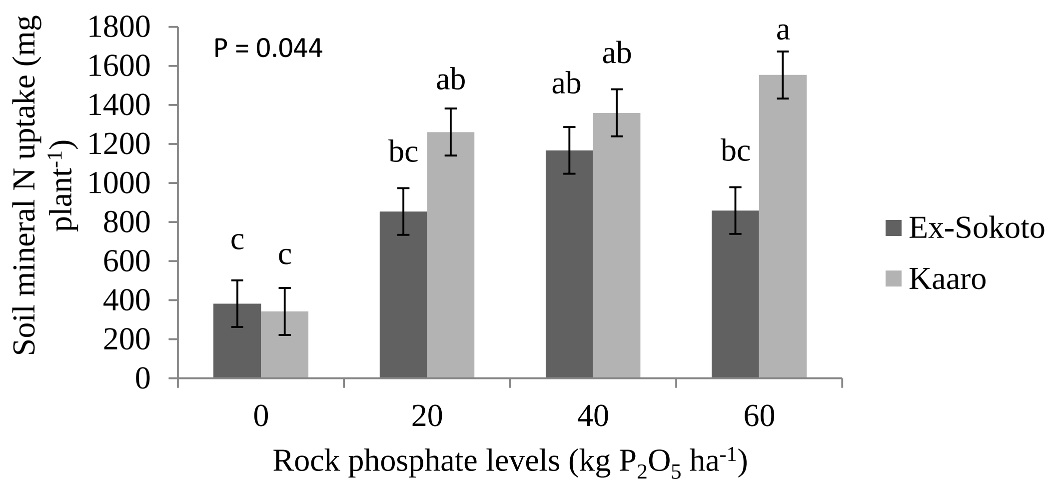

Figure 4. 2. 3: Effect of interaction between the landraces and rock phosphate levels on soil mineral N uptake of Bambara groundnut. Error bars are SEM values. Bars with the same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test.

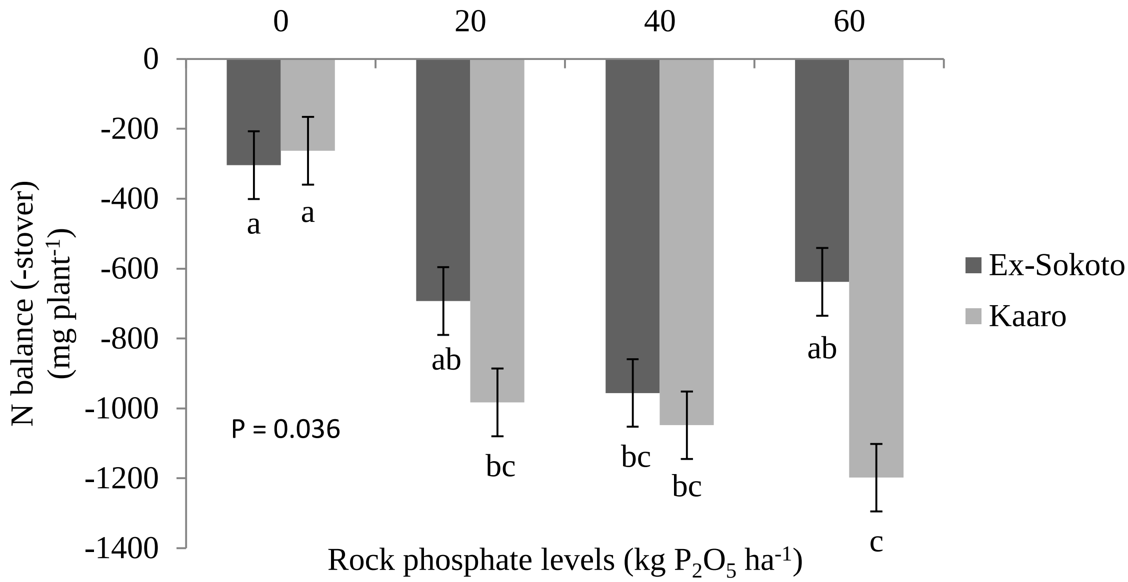

Figure 4. 2. 4: Effect of interaction between the landraces and rock phosphate levels on N balance (-stover) of Bambara groundnut. Error bars are SEM values. Bars with the same letter(s) are not significantly different at 5 % level using Duncan's Multiple Range Test.

4.3 Experiment 3: Growth, yield and N fixation of Bambara groundnut landraces as influenced by biochar and rock phosphate levels.

4.3.1 Plant height

Plant height of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.1.

Effect of biochar

In the first trial, the plant height of the crop in the biochar treatments at 4 (12.2-12.4 cm) and 6 (15.3-15.9 cm) weeks after sowing (WAS) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, at 8 WAS, application of biochar significantly ($P<0.05$) increased the plant height of the crop from 20.4 cm recorded where no biochar was applied to 22.5 cm. However, in the second trial, application of biochar significantly ($P<0.05$) increased the plant height of the crop from 14.0, 15.2 and 18.0 cm recorded at 4, 6 and 8 WAS, respectively where no biochar was applied to 14.7, 16.5 and 19.7 cm, respectively. In the combined, the plant height of the crop at 4 WAS (13.2-13.4 cm) was not significantly ($P>0.05$) influenced by the application of biochar. However, at 6 and 8 WAS, application of biochar significantly ($P<0.05$) increased the plant height of the crop from 15.3 and 19.2 cm, respectively recorded where no biochar was applied to 16.2 and 21.1 cm, respectively.

Effect of landrace

In the first trial, Ex-Sokoto landrace recorded plant height of 12.3, 15.4 and 22.0 cm at 4, 6 and 8 WAS, respectively which was not significantly ($P>0.05$) different from 12.3, 15.8 and 20.9 cm, respectively recorded by Kaaro landrace. In the second trial, Kaaro landrace was significantly ($P<0.05$) higher (15.0 cm) in plant height at 4 WAS than Ex-Sokoto landrace which recorded 13.7 cm. However, the plant height of the crop at 6 (15.5-16.2) and 8 WAS (18.8-18.9 cm) was not significantly (P>0.05) different between the landraces. In the combined, at 4 WAS, Kaaro landrace recorded plant height of 13.6 cm which was significantly (P<0.05) higher than 13.0 cm recorded by Ex-Sokoto landrace. However, the plant height of the crop at 6 (15.5-16.0 cm) and 8 WAS (19.8-20.5 cm) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

In the first trial, the plant height of the crop recorded at 4, 6 and 8 WAS in the rock phosphate treatments ranged from 12.1-12.5, 15.1-16.1 and 21.1-21.7 cm, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the plant height ranged from 14.0-14.7, 15.6-16.1 and 18.2-19.5 cm at 4, 6 and 8 WAS, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the plant height at 4, 6 and 8 WAS ranged from 13.1-13.6, 15.5-15.9 and 19.8-20.6 cm, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No Significant (P>0.05) interaction between the treatments on the plant height of the crop was observed during the trials.

Table 4. 3. 1: Plant height of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatment	Plant height (cm)								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	12.4	15.3	20.4b	14.0b	15.2b	18.0b	13.2	15.3b	19.2b
10	12.2	15.9	22.5a	14.7a	16.5a	19.7a	13.4	16.2a	21.1a
SEM	0.289	0.467	0.472	0.249	0.300	0.379	0.191	0.277	0.303
P value	0.579	0.351	0.005	0.036	0.004	0.005	0.316	0.015	<.001
Landrace (L)									
Ex-Sokoto	12.3	15.4	22.0	13.7b	15.5	18.9	13.0b	15.5	20.5
Kaaro	12.3	15.8	20.9	15.0a	16.2	18.8	13.6a	16.0	19.8
SEM	0.289	0.467	0.472	0.249	0.300	0.379	0.191	0.277	0.303
P value	0.960	0.493	0.129	0.001	0.127	0.729	0.026	0.157	0.156
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	12.3	15.1	21.6	14.3	16.1	19.3	13.3	15.6	20.5
20	12.3	15.8	21.1	14.4	16.1	18.4	13.3	15.9	19.8
40	12.1	16.1	21.4	14.0	15.8	18.2	13.1	15.9	19.8
60	12.5	15.5	21.7	14.7	15.6	19.5	13.6	15.5	20.6
SEM	0.409	0.660	0.668	0.352	0.425	0.536	0.270	0.392	0.428
P value	0.912	0.748	0.929	0.658	0.792	0.245	0.600	0.844	0.396
Interaction (P values)									
B X L	0.450	0.240	0.081	0.317	0.180	0.302	0.933	0.792	0.454
B X RP	0.415	0.877	0.491	0.118	0.926	0.759	0.198	0.823	0.850
L X RP	0.780	0.676	0.054	0.826	0.069	0.275	0.721	0.555	0.440
B X L X RP	0.515	0.314	0.230	0.659	0.586	0.257	0.439	0.201	0.544

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.2 Number of leaves per plant

Number of leaves per plant of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.2.

Effect of biochar

In the first trial, at 6 WAS, application of biochar significantly ($P<0.05$) increased the number of leaves per plant from 38.4 leaves recorded where no biochar was applied to 42.3 leaves. However, the number of leaves per plant at 4 (13.2-14.1) and 8 WAS (58.5-62.9) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. In the second trial, application of biochar significantly ($P<0.05$) increased the number of leaves per plant from 30.0, 43.1 and 46.1 leaves recorded at 4, 6 and 8 WAS, respectively in the treatments where no biochar was applied to 34.3, 55.3 and 53.3 leaves, respectively. Similarly, in the combined, application of biochar significantly ($P<0.05$) increased the number of leaves per plant from 21.6, 40.8 and 52.3 leaves recorded where no biochar was applied at 4, 6 and 8 WAS, respectively to 24.2, 48.8 and 60.6 leaves, respectively.

Effect of landrace

In the first trial, the number of leaves per plant at 4 (13.4-13.9), 6 (39.8-41.0) and 8 WAS (60.4-60.9) was not significantly ($P>0.05$) different between the landraces. In the second trial, Kaaro landrace was significantly ($P<0.05$) higher (33.9) in number of leaves per plant at 4 WAS than Ex-Sokoto landrace which recorded 30.4 leaves per plant. However, the number of leaves per plant at 6 (48.3-50.1) and 8 WAS (51.4-53.0) was not significantly ($P>0.05$) different between the landraces. Similarly, in the combined, the number of leaves per plant at 4 (22.2-23.6), 6 (44.0-45.4) and 8 WAS (56.1-56.7) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

In the first trial, the number of leaves per plant in the rock phosphate treatments at 4, 6 and 8 WAS ranged from 13.2-14.3, 37.8-42.2 and 59.0-61.9 leaves, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the number of leaves per plant at 4, 6 and 8 WAS ranged from 30.4-33.8, 47.5-51.8 and 50.6-54.4 leaves, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the number of leaves per plant at 4 (21.9-24.0), 6 (43.8-46.1) and 8 WAS (56.2-56.9) was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the number of leaves per plant was observed during the trials.

Table 4. 3. 2: Number of leaves per plant of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatment	Number of leaves per plant								
	First trial			Second trial			Combined		
	4 WAS	6 WAS	8 WAS	4 WAS	6 WAS	8 WAS	4 WAS	6 WAS	8 WAS
Biochar (B) (t ha^{-1})									
0	13.2	38.4b	58.5	30.0b	43.1b	46.1b	21.6b	40.8b	52.3b
10	14.1	42.3a	62.9	34.3a	55.3a	53.3a	24.2a	48.8a	60.6a
SEM	0.421	1.242	2.72	1.141	1.92	1.91	0.608	1.143	1.66
P value	0.152	0.033	0.261	0.012	<.001	<.001	0.004	<.001	<.001
Landrace (L)									
Ex-Sokoto	13.9	39.8	60.9	30.4b	48.3	51.4	22.2	44.0	56.1
Kaaro	13.4	41.0	60.4	33.9a	50.1	53.0	23.6	45.5	56.7
SEM	0.421	1.242	2.72	1.141	1.92	1.91	0.608	1.143	1.66
P value	0.370	0.482	0.898	0.038	0.524	0.542	0.091	0.357	0.805
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	13.2	37.8	60.0	31.8	49.8	52.8	22.5	43.8	56.4
20	13.5	41.1	61.9	30.4	47.7	50.7	21.9	44.4	56.3
40	13.7	42.2	61.8	32.7	47.5	50.6	23.2	44.8	56.2
60	14.3	40.4	59.0	33.8	51.8	54.8	24.0	46.1	56.9
SEM	0.595	1.756	3.85	1.613	2.72	2.70	0.860	1.617	2.35
P value	0.633	0.364	0.939	0.501	0.640	0.647	0.356	0.778	0.996
Interaction (P values)									
B X L	0.194	0.374	0.430	0.387	0.985	0.951	0.718	0.626	0.492
B X RP	0.254	0.168	0.966	0.209	0.550	0.550	0.396	0.398	0.677
L X RP	0.359	0.799	0.611	0.491	0.911	0.889	0.746	0.831	0.915
B X L X RP	0.127	0.079	0.732	0.762	0.978	0.966	0.466	0.351	0.756

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.3 Leaf area per plant (LA)

Leaf area per plant of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.3.

Effect of biochar

In the first trial, application of biochar significantly ($P<0.05$) increased the leaf area per plant at 4 WAS from 77.6 cm^2 recorded where no biochar was applied to 94.3 cm^2. However, the leaf area per plant at 6 (960-1102 cm^2) and 8 WAS (1943-1991 cm^2) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. In the second trial, the leaf area per plant at 4 WAS (745-856 cm^2) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, at 6 and 8 WAS, application of biochar significantly ($P<0.05$) increased the leaf area of the crop from 1160 and 1237 cm^2, respectively recorded where no biochar was applied to 1580 and 1665 cm^2, respectively. Similarly, in the combined, the leaf area of the crop at 4 WAS (411-475 cm^2) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, at 6 and 8 WAS, application of biochar significantly ($P<0.05$) increased the leaf area of the crop from 1060 and 1590 cm^2, respectively obtained in the treatments where no biochar was applied to 1341 and 1828 cm^2, respectively.

Effect of landrace

In the first trial, Kaaro landrace was significantly ($P<0.05$) higher (94.7 cm^2) in leaf area per plant at 4 WAS than Ex-Sokoto landrace which recorded 77.2 cm^2. However, the leaf area of the crop at 6 (928-1134 cm^2) and 8 WAS (1784-2149 cm^2) was not significantly ($P>0.05$) different between the landraces. In the second trial, Kaaro landrace recorded leaf area of 925, 1505 and 1591 cm^2 at 4, 6 and 8 WAS, respectively which was significantly ($P<0.05$) higher than 675, 1235 and 1310 cm^2, respectively recorded by Ex-Sokoto landrace. Similarly, in the combined, Kaaro landrace recorded leaf area of 510, 1319 and 1870 cm^2 at 4, 6 and 8 WAS, respectively which was significantly ($P<0.05$) higher than 376, 1081 and 1547 cm^2, respectively recorded by Ex-Sokoto landrace.

Effect of rock phosphate

In the first trial, the leaf area per plant at 4, 6 and 8 WAS ranged from 74.0-95.9, 889-1146 and 1899-2061 cm^2, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the leaf area per plant at 4, 6 and 8 WAS ranged from 742-857, 1182-1514 and 1255-1601 cm^2 per plant, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the leaf area per plant ranged from 419-576, 1164-1270 and 1619-1763 cm^2 at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the leaf area per plant of the crop was observed during the trials.

Table 4. 3. 3: Leaf area per plant of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatment	Leaf area per plant (cm^2)								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	77.6b	960	1943	745	1160b	1237b	411	1060b	1590b
10	94.3a	1102	1991	856	1580a	1665a	475	1341a	1828a
SEM	5.59	75.3	135.9	50.5	85.5	87.4	25.4	56.9	80.8
P value	0.043	0.193	0.804	0.129	0.002	0.002	0.079	<.001	0.041
Landrace (L)									
Ex-Sokoto	77.2b	928	1784	675b	1235b	1310b	376b	1081b	1547b
Kaaro	94.7a	1134	2149	925a	1505a	1591a	510a	1319a	1870a
SEM	5.59	75.3	135.9	50.5	85.5	87.4	25.4	56.9	80.8
P value	0.035	0.062	0.067	0.001	0.033	0.030	<.001	0.004	0.006
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	79.8	889	1899	830	1449	1530	455	1169	1715
20	74.0	1062	2061	773	1335	1417	423	1198	1739
40	95.9	1146	1982	742	1182	1255	419	1164	1619
60	94.0	1026	1924	857	1514	1601	576	1270	1763
SEM	7.90	106.4	192.1	71.4	120.9	123.6	35.9	80.5	114.2
P value	0.160	0.402	0.935	0.659	0.247	0.237	0.644	0.744	0.821
Interaction (P values)									
B X L	0.695	0.440	0.465	0.765	0.605	0.626	0.798	0.901	0.723
B X RP	0.604	0.132	0.601	0.164	0.543	0.530	0.175	0.459	0.674
L X RP	0.452	0.890	0.950	0.514	0.774	0.739	0.543	0.844	0.802
B X L X RP	0.705	0.070	0.795	0.676	0.879	0.863	0.598	0.203	0.745

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.4 Leaf area index (LAI)

Leaf area index of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.4.

Effect of biochar

In the first trial, application of biochar significantly ($P<0.05$) increased the leaf area index of the crop at 4 WAS from 0.078 per plant to 0.094 per plant. However, the leaf area index of the crop at 6 (0.960-1.102) and 8 WAS (1.943-1.991) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. In the second trial, the leaf area index of the crop at 4 WAS (0.745-0.856) not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, at 6 and 8 WAS, application of biochar significantly ($P<0.05$) increased the leaf area index of the crop from 1.160 and 1.237, respectively recorded where no biochar was applied to 1.580 and 1.665, respectively. Similarly, in the combined, the leaf area index of the crop at 4 WAS (0.411-0.475) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, application of biochar significantly ($P<0.05$) increased the leaf area index of the crop at 6 and 8 WAS from 1.060 and 1.590, respectively recorded where no biochar was applied to 1.341 and 1.828, respectively.

Effect of landrace

In the first trial, Kaaro landrace was significantly ($P<0.05$) higher (0.095) in leaf area index at 4 WAS than Ex-Sokoto landrace which recorded leaf area index of 0.077. However, the leaf area index of the landraces at 6 (0.928-1.134) and 8 WAS (1.784-2.149) was not significantly ($P>0.05$) different between the landraces. In the second trial, Kaaro landrace recorded leaf area index of 0.925, 1.505 and 1.591 at 4, 6 and

8 WAS, respectively that was significantly (P<0.05) higher than 0.675, 1.235 and 1.310, respectively recorded by Ex-Sokoto landrace. Similarly, in the combined, Kaaro landrace recorded leaf area index of 0.510, 1.319 and 1.870 at 4, 6 and 8 WAS, respectively which was significantly (P<0.05) higher than 0.376, 1.081 and 1.547, respectively recorded by Ex-Sokoto landrace.

Effect of rock phosphate

In the first trial, the leaf area index of the crop in the rock phosphate treatments ranged from 0.074-0.096, 0.889-1.146 and 1.899-2.061 at 4, 6 and 8 WAS, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Likewise, in the second trial, the leaf area index of the crop in the rock phosphate treatments ranged from 0.742-0.857, 1.182-1.514 and 1.255-1.601 at 4, 6 and 8 WAS, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Similarly, in the combined, the leaf area index of the crop in the rock phosphate treatments ranged from 0.419-0.476, 1.164-1.270 and 1.619- 1.763 at 4, 6 and 8 WAS, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interactions

No significant (P>0.05) interaction between the treatments on the leaf area index of the crop was observed during the trials.

Table 4. 3. 4: Leaf area index of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Leaf area index (LAI)								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	0.078b	0.960	1.943	0.745	1.160b	1.237b	0.411	1.060b	1.590b
10	0.094a	1.102	1.991	0.856	1.580a	1.665a	0.475	1.341a	1.828a
SEM	0.0056	0.0753	0.1359	0.0505	0.0855	0.0874	0.0254	0.0569	0.0808
P value	0.043	0.193	0.804	0.129	0.002	0.002	0.079	<.001	0.041
Landrace (L)									
Ex-Sokoto	0.077b	0.928	1.784	0.675b	1.235b	1.310b	0.376b	1.081b	1.547b
Kaaro	0.095a	1.134	2.149	0.925a	1.505a	1.591a	0.510a	1.319a	1.870a
SEM	0.0056	0.0753	0.1359	0.0505	0.0855	0.0874	0.0254	0.0569	0.0808
P value	0.035	0.062	0.067	0.001	0.033	0.030	<.001	0.004	0.006
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	0.080	0.889	1.899	0.830	1.449	1.530	0.455	1.169	1.715
20	0.074	1.062	2.061	0.773	1.335	1.417	0.423	1.198	1.739
40	0.096	1.146	1.962	0.742	1.182	1.255	0.419	1.164	1.619
60	0.094	1.026	1.924	0.857	1.514	1.601	0.476	1.270	1.763
SEM	0.0079	0.1064	0.1921	0.0714	0.1209	0.1236	0.0359	0.0805	0.1142
P value	0.160	0.402	0.935	0.659	0.247	0.237	0.644	0.774	0.821
Interactions									
B X L	0.695	0.440	0.465	0.765	0.605	0.626	0.798	0.901	0.723
B X RP	0.604	0.132	0.601	0.164	0.543	0.530	0.175	0.459	0.674
L X RP	0.452	0.890	0.950	0.514	0.774	0.739	0.543	0.844	0.802
B X L X RP	0.705	0.070	0.795	0.676	0.879	0.863	0.598	0.203	0.745

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.5 Chlorophyll content (SPAD value)

Chlorophyll content of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.5.

Effect of biochar

In the first trial, the chlorophyll content of the crop at 4 (52.1-52.6), 6 (52.7-53.5) and 8 WAS (52.9-53.5) was not significantly (P>0.05) influenced by the application of biochar on the crop. Similarly, in the second trial, the chlorophyll content of the crop at 4 (49.5-49.7), 6 (49.0-49.1) and 8 WAS (55.6-56.8) was not significantly (P>0.05) influenced by the application of biochar on the crop. Likewise, in the combined, the chlorophyll content of the crop ranged from 50.8-51.1, 50.9-51.3 and 54.6-54.9 at 4, 6 and 8 WAS, respectively and was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

In the first trial, the chlorophyll content of the crop at 4 (52.1-52.6), 6 (52.6-53.6) and 8 WAS (52.2-54.3) was not significantly (P>0.05) different between the landraces. In the second trial, Kaaro landrace was significantly (P<0.05) higher (49.8) in chlorophyll content at 6 WAS than Ex-Sokoto landrace which recorded 48.3. However, the chlorophyll content of the landraces at 4 (49.5-49.6) and 8 WAS (55.9-56.5) was not significantly (P>0.05) different between the landraces. Similarly, in the combined, at 6 WAS kaaro landrace was significantly (P<0.05) higher (51.7) in chlorophyll content than Ex-Sokoto landrace which recorded chlorophyll content of 50.4. However, the chlorophyll content of the landraces at 4 (50.8-51.1) and 8 WAS (54.3-55.1) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

In the first trial, the chlorophyll content of the crop in the rock phosphate treatments ranged from 51.8-53.1, 52.2-54.1 and 51.7-54.9 at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the chlorophyll content of the crop ranged from 48.6-50.2, 48.3-49.9 and 55.6-57.3 at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the chlorophyll content of the crop ranged from 50.5-51.4, 50.5-51.8 and 53.7-55.3 at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the chlorophyll content of the crop was observed during the trials.

Table 4. 3. 5: Chlorophyll content (SPAD value) of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Chlorophyll content (SPAD value)								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	52.6	53.5	53.5	49.7	49.1	55.6	51.1	51.3	54.6
10	52.1	52.7	52.9	49.5	49.0	56.8	50.8	50.9	54.9
SEM	0.577	0.720	0.860	0.670	0.509	0.799	0.442	0.441	0.587
P value	0.551	0.460	0.628	0.817	0.963	0.298	0.571	0.526	0.719
Landrace (L)									
Ex-Sokoto	52.6	52.6	54.3	49.6	48.3b	55.9	51.1	50.4b	55.1
Kaaro	52.1	53.6	52.2	49.5	49.8a	56.5	50.8	51.7a	54.3
SEM	0.577	0.720	0.860	0.670	0.509	0.799	0.442	0.441	0.587
P value	0.578	0.328	0.104	0.920	0.046	0.597	0.659	0.048	0.391
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	53.1	52.2	51.7	49.6	49.9	55.6	51.4	51.0	53.7
20	52.1	54.1	53.3	50.2	49.5	57.3	51.1	51.8	55.3
40	52.4	53.4	54.9	48.6	48.5	55.8	50.5	50.9	55.3
60	51.8	52.7	53.0	49.9	48.3	56.0	50.9	50.5	54.5
SEM	0.816	1.019	1.216	0.947	0.720	1.130	0.625	0.624	0.830
P value	0.712	0.560	0.344	0.624	0.376	0.690	0.755	0.535	0.429
Interactions									
B X L	0.350	0.563	0.599	0.635	0.774	0.592	0.329	0.757	0.451
B X RP	0.423	0.488	0.580	0.636	0.344	0.860	0.360	0.935	0.976
L X RP	0.331	0.388	0.252	0.985	0.412	0.688	0.825	0.859	0.235
B X L X RP	0.400	0.354	0.760	0.199	0.511	0.218	0.150	0.665	0.796

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.6 Normalised difference vegetation index (NDVI)

Normalised difference vegetation index (NDVI) of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.6.

Effect of biochar

In the first trial, the NDVI of the crop at 4 (0.295-0.312), 6 (0.543-0.571) and 8 WAS (0.760-0.788) was not significantly influenced ($P>0.05$) by the application of biochar on the crop. In the second trial, the treatments that received biochar application recorded NDVI of 0.600, 0.749 and 0.728 at 4, 6 and 8 WAS, respectively which was significantly ($P<0.05$) higher than 0.530, 0.653 and 0.650, respectively recorded in the treatments where no biochar was applied. Similarly, in the combined, application of biochar significantly ($P<0.05$) increased the NDVI of the crop at 4, 6 and 8 WAS from 0.413, 0.598 and 0.705, respectively recorded in the treatments where no biochar was applied to 0.457, 0.660 and 0.758, respectively.

Effect of landrace

In the first trial, the NDVI of the crop at 4 (0.299-0.308), 6 (0.542-0.573) and 8 WAS (0.772-0.777) was not significantly ($P>0.05$) different between the landraces. Similarly, in the second trial, the NDVI of the landraces ranged from 0.560-0.580, 0.681-0.721 and 0.680-0.699 at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) different between the landraces. In the combined, Kaaro landrace recorded NDVI of 0.647 at 6 WAS which was significantly ($P<0.05$) higher than 0.611 recorded by Ex-Sokoto landrace. However, at 4 (0.427-0.443) and 8 WAS (0.726-0.738) the NDVI of the crop was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

In the first trial, the NDVI of the crop at 4, 6 and 8 WAS recorded in the rock phosphate treatments ranged from 0.298-0.308, 0.551-0.566 and 0.768-0.778, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the NDVI of the crop at 4, 6 and 8 WAS recorded in the rock phosphate treatments ranged from 0.560-0.580, 0.681-0.730 and 0.672-0.705, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the NDVI of the crop at 4, 6 and 8 WAS ranged from 0.429-0.441, 0.619-0.640 and 0.725-0.737, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the NDVI of the crop was observed during the trials.

Table 4. 3. 6: Normalised difference vegetation index NDVI of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Normalised difference vegetation index (NDVI)								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	0.295	0.543	0.760	0.530b	0.653b	0.650b	0.413b	0.598b	0.705b
10	0.312	0.571	0.788	0.600a	0.749a	0.728a	0.457a	0.660a	0.758a
SEM	0.0082	0.0182	0.0112	0.0181	0.0150	0.0162	0.0099	0.0118	0.0099
P value	0.159	0.288	0.084	0.008	<.001	0.002	0.002	<.001	<.001
Landrace (L)									
Ex-Sokoto	0.299	0.542	0.772	0.560	0.681	0.680	0.427	0.611b	0.726
Kaaro	0.308	0.573	0.777	0.580	0.721	0.699	0.443	0.647a	0.738
SEM	0.0082	0.0182	0.0112	0.0181	0.0150	0.0162	0.0099	0.0118	0.0099
P value	0.434	0.235	0.754	0.395	0.070	0.400	0.270	0.037	0.381
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	0.305	0.555	0.773	0.580	0.703	0.692	0.441	0.629	0.732
20	0.305	0.558	0.778	0.560	0.681	0.689	0.434	0.619	0.734
40	0.298	0.566	0.778	0.570	0.689	0.672	0.434	0.628	0.725
60	0.308	0.551	0.768	0.560	0.730	0.705	0.429	0.640	0.737
SEM	0.0116	0.0258	0.0158	0.0256	0.0213	0.0230	0.0140	0.0167	0.0139
P value	0.935	0.980	0.967	0.896	0.395	0.785	0.945	0.844	0.938
Interactions									
B X L	0.394	0.089	0.103	0.759	0.907	0.760	0.941	0.204	0.485
B X RP	0.075	0.895	0.144	0.854	0.411	0.326	0.877	0.831	0.898
L X RP	0.368	0.748	0.391	0.507	0.676	0.233	0.349	0.723	0.118
BX L X RP	0.794	0.125	0.360	0.924	0.684	0.993	0.809	0.181	0.749

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.7 Leaf photosynthesis

Leaf photosynthesis of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.7.

Effect of biochar

In the first trial, the leaf photosynthesis of the crop in the biochar treatments at 4 (23.86-25.06 μmol CO_2 m^{-2} s^{-1}), 6 (28.34-28.73 μmol CO_2 m^{-2} s^{-1}) and 8WAS (28.31-29.37 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop. In the second trial, application of biochar significantly (P<0.05) increased the leaf photosynthesis of the crop at 4 WAS from 49.56 μmol CO_2 m^{-2} s^{-1} recorded where no biochar was applied to 56.68 μmol CO_2 m^{-2} s^{-1}. However, application of biochar significantly (P<0.05) decreased the leaf photosynthesis of the crop at 8 WAS from 67.22 μmol CO_2 m^{-2} s^{-1} recorded where no biochar was applied to 63.92 μmol CO_2 m^{-2} s^{-1}. The leaf photosynthesis of the crop at 6 WAS (58.24-59.63 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop. In the combined, the leaf photosynthesis of the crop at 4 (35.87-36.71 μmol CO_2 m^{-2} s^{-1}) and 6 WAS (43.49-43.99 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop. However, application of biochar significantly (P>0.05) decreased the leaf photosynthesis of the crop at 8 WAS from 48.29 μmol CO_2 m^{-2} s^{-1} recorded in the treatments where no biochar was applied to 46.11 μmol CO_2 m^{-2} s^{-1}.

Effect of landrace

In the first trial, Ex-Sokoto landrace was significantly (P<0.05) higher (25.97 μmol CO_2 m^{-2} s^{-1}) in leaf photosynthesis at 4 WAS than Kaaro landrace which recorded leaf photosynthesis of 22.95 μmol CO_2 m^{-2} s^{-1}. However, the leaf photosynthesis of the landraces at 6 (27.79-29.28 μmol CO_2 m^{-2} s^{-1}) and 8 WAS (28.28-29.39 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) different between the landraces. Similarly, in the second trial, the leaf photosynthesis of the crop at 4 (47.27-48.98 μmol CO_2 m^{-2} s^{-1}), 6 (58.35-59.52 μmol CO_2 m^{-2} s^{-1}) and 8 WAS (65.30-65.84 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) different between the landraces. In the combined, kaaro landrace was significantly (P<0.05) higher (44.40 μmol CO_2 m^{-2} s^{-1}) in leaf photosynthesis at 6 WAS than Ex-Sokoto landrace (43.07 μmol CO_2 m^{-2} s^{-1}). However, the leaf photosynthesis of the crop at 4 (35.96-36.62 μmol CO_2 m^{-2} s^{-1}) and 8 WAS (46.79-47.62 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

In the first trial, the leaf photosynthesis of the crop at 4 (23.58-25.44 μmol CO_2 m^{-2} s^{-1}), 6 (28.29-28.74 μmol CO_2 m^{-2} s^{-1}) and 8 WAS (27.80-30.41 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the leaf photosynthesis of the crop at 4 (47.68-48.49 μmol CO_2 m^{-2} s^{-1}), 6 (58.26-59.01 μmol CO_2 m^{-2} s^{-1}) and 8 WAS (65.33-65.87 μmol CO_2 m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of rock phosphate on the crop. Likewise, in the combined the leaf photosynthesis of the crop at 4, 6 and 8 WAS ranged from 36.04-36.72, 43.50-44.09 and 46.64-47.87 μmol CO_2 m^{-2} s^{-1}, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant (P>0.05) interaction between the treatments on the leaf photosynthesis of the crop was observed during the trials.

Table 4. 3. 7: Leaf Photosynthesis of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Leaf photosynthesis (µmol CO_2 m^{-2} s^{-1})								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	23.86	28.73	29.37	49.56a	58.24	67.22a	36.71	43.49	48.29a
10	25.06	28.34	28.31	56.68b	59.63	63.92b	35.87	43.99	46.11b
SEM	0.547	0.570	0.685	0.648	0.502	0.412	0.424	0.380	0.400
P value	0.133	0.629	0.282	0.004	0.059	<.001	0.164	0.355	<.001
Landrace (L)									
Ex-Sokoto	25.97a	27.79	28.28	47.27	58.35	65.30	36.62	43.07b	46.79
Kaaro	22.95b	29.28	29.39	48.98	59.52	65.84	35.96	44.40a	47.62
SEM	0.547	0.570	0.685	0.648	0.502	0.412	0.424	0.380	0.400
P value	<.001	0.074	0.262	0.072	0.110	0.361	0.278	0.016	0.150
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	24.15	28.65	27.80	48.30	59.54	65.49	36.23	44.09	46.64
20	25.44	28.48	29.12	48.01	58.92	65.59	36.72	43.70	47.36
40	24.68	28.74	30.41	47.68	58.26	65.33	36.18	43.50	47.87
60	23.58	28.29	28.02	48.49	59.01	65.87	36.04	43.65	46.94
SEM	0.773	0.806	0.969	0.916	0.709	0.582	0.599	0.537	0.565
P value	0.387	0.981	0.227	0.928	0.656	0.927	0.862	0.880	0.453
Interactions									
B X L	0.339	0.592	0.932	0.880	0.516	0.444	0.611	0.978	0.638
B X RP	0.449	0.341	0.311	0.931	0.604	0.933	0.736	0.211	0.566
L X RP	0.593	0.810	0.881	0.665	0.706	0.401	0.469	0.800	0.155
B X L X RP	0.056	0.774	0.074	0.798	0.681	0.716	0.561	0.631	0.117

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.8 Stomatal conductance

Stomatal conductance of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.8.

Effect of biochar

In the first trial, the stomatal conductance of the crop at 4 (1.089-1.182 mol H_2O m^{-2} s^{-1}), 6 (1.320-1.350 mol H_2O m^{-2} s^{-1}) and 8 WAS (1.268-1.274 mol H_2O m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop. Similarly, in the second trial, the stomatal conductance of the crop at 4 (1.111-1.266 mol H_2O m^{-2} s^{-1}) and 6 WAS (0.626-0.678 mol H_2O m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop. However, application of biochar significantly (P<0.05) decreased the stomatal conductance of the crop at 8 WAS in the second trial from 0.802 mol H_2O m^{-2} s^{-1} recorded where no biochar was applied to 0.713 mol H_2O m^{-2} s^{-1}. In the combined, the stomatal conductance of the crop in the biochar treatments at 4 (1.135-1.177 mol H_2O m^{-2} s^{-1}), 6 (0.988-0.999 mol H_2O m^{-2} s^{-1}) and 8 WAS (0.994-1.035 mol H_2O m^{-2} s^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

In the first trial, Ex-Sokoto landrace was significantly (P<0.05) higher (1.358 mol H_2O m^{-2} s^{-1}) in stomatal conductance at 4 WAS than Kaaro (0.913 mol H_2O m^{-2} s^{-1}) landrace. However, the stomatal conductance of the crop at 6 (1.298-1.372 mol H_2O m^{-2} s^{-1}) and 8 WAS (1.237-1.306 mol H_2O m^{-2} s^{-1}) was not significantly (P>0.05) different between the landraces. Similarly, in the second trial, the stomatal conductance of the crop at 4 (1.118-1.259 mol H_2O m^{-2} s^{-1}), 6 (0.622-0.683 mol H_2O m^{-2} s^{-1}) and 8 WAS (0.740-0.775 mol H_2O m^{-2} s^{-1}) was not significantly (P>0.05) different between the landraces. In the combined, Ex-Sokoto landrace was significantly ($P<0.05$) higher (1.238 mol H_2O m^{-2} s^{-1}) in stomatal conductance at 4 WAS than Kaaro (1.086 mol H_2O m^{-2} s^{-1}) landrace. However, the stomatal conductance of the crop at 6 (0.990-0.997 mol H_2O m^{-2} s^{-1}) and 8 WAS (0.988-1.041 mol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

In the first trial, the stomatal conductance of the crop in the rock phosphate treatments ranged from 1.051-1.265, 1.285-1.378 and 1.249-1.317 mol H_2O m^{-2} s^{-1} at 4, 6 and 8 WAS, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the stomatal conductance of the crop at 4 (1.112-1.302 mol H_2O m^{-2} s^{-1}), 6 (0.617-0.685 mol H_2O m^{-2} s^{-1}) and 8 WAS (0.710-0.779 mol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined, the stomatal conductance of the crop at 4 (1.117-1.224 mol H_2O m^{-2} s^{-1}), 6 (0.954-1.032 mol H_2O m^{-2} s^{-1}) and 8 WAS (0.979-1.040 mol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interactions

No significant ($P>0.05$) interaction between the treatments on the stomatal conductance of the crop was observed during the trial.

Table 4. 3. 8: Stomatal conductance of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Stomatal conductance (mol H_2O m^{-2} s^{-1})								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	1.182	1.320	1.268	1.111	0.678	0.802a	1.135	0.999	1.035
10	1.089	1.350	1.274	1.266	0.626	0.713b	1.177	0.988	0.994
SEM	0.0468	0.0584	0.0439	0.0535	0.0264	0.0184	0.0355	0.0320	0.0238
P value	0.171	0.720	0.923	0.050	0.171	0.002	0.542	0.805	0.223
Landrace (L)									
Ex-Sokoto	1.358a	1.298	1.237	1.118	0.683	0.740	1.238a	0.990	0.988
Kaaro	0.913b	1.372	1.306	1.259	0.622	0.775	1.086b	0.997	1.041
SEM	0.0468	0.0584	0.0439	0.0535	0.0264	0.0184	0.0355	0.0320	0.0238
P value	<.001	0.376	0.274	0.072	0.112	0.188	0.004	0.885	0.127
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	1.051	1.378	1.260	1.302	0.685	0.779	1.176	1.032	1.020
20	1.265	1.336	1.249	1.182	0.685	0.710	1.224	1.010	0.979
40	1.151	1.285	1.317	1.112	0.623	0.763	1.131	0.954	1.040
60	1.075	1.341	1.260	1.159	0.617	0.778	1.117	0.979	1.019
SEM	0.0662	0.0826	0.0621	0.0757	0.0373	0.0261	0.0503	0.0453	0.0337
P value	0.119	0.883	0.861	0.349	0.396	0.217	0.438	0.634	0.637
Interactions									
B X L	0.462	0.900	0.799	0.592	0.076	0.170	0.934	0.386	0.760
B X RP	0.185	0.204	0.499	0.932	0.209	0.510	0.288	0.301	0.496
L X RP	0.456	0.707	0.422	0.987	0.202	0.322	0.794	0.474	0.461
B X L X RP	0.063	0.942	0.399	0.986	0.505	0.501	0.410	0.747	0.604

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.9 *Leaf transpiration*

Leaf transpiration of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.9.

Effect of biochar

In the first trial, application of biochar significantly ($P<0.05$) increased the transpiration of the crop at 4 WAS from 8.101 mmol H_2O m^{-2} s^{-1} recorded where no biochar was applied to 8.483 mmol H_2O m^{-2} s^{-1}. However, the transpiration of the crop at 6 (8.290-8.710 mmol H_2O m^{-2} s^{-1}) and 8 WAS (7.940-8.120 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. In the second trial, the transpiration of the crop at 4 WAS (9.622-9.810 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of biochar on the crop. However, application of biochar significantly ($P<0.05$) decreased the transpiration of the crop at 6 and 8 WAS from 6.138 and 5.754 mmol H_2O m^{-2} s^{-1}, respectively recorded where no biochar was applied to 5.374 and 5.571 mmol H_2O m^{-2} s^{-1}, respectively. In the combined, application of biochar significantly ($P<0.05$) increased the transpiration of the crop at 4 WAS from 8.862 mmol H_2O m^{-2} s^{-1} recorded where no biochar was applied to 9.147 mmol H_2O m^{-2} s^{-1}. However, the transpiration of the crop at 6 (7.029-7.212 mmol H_2O m^{-2} s^{-1}) and 8 WAS (6.844-6.847 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

In the first trial, Ex-Sokoto landrace was significantly ($P <0.05$) higher (8.710 mmol H_2O m^{-2} s^{-1}) in transpiration at 6 WAS than Kaaro landrace which recorded 8.260 mmol H_2O m^{-2} s^{-1}. However, the transpiration of the crop at 4 (8.144-8.440 mmol

H_2O m^{-2} s^{-1}) and 8 WAS (7.980-8.080 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) different between the landraces. In the second trial, Kaaro landrace was significantly ($P<0.05$) higher in transpiration at 4 (9.976 mmol H_2O m^{-2} s^{-1}) and 8 WAS (5.780 mmol H_2O m^{-2} s^{-1}) than Ex-Sokoto landrace which recorded 9.457 and 5.545 mmol H_2O m^{-2} s^{-1}, respectively. However, the transpiration of the landraces at 6 WAS (5.693-5.819 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) different between the landraces. In the combined, the transpiration of the crop at 4 (8.948-9.060 mmol H_2O m^{-2} s^{-1}), 6 (7.042-7.199 mmol H_2O m^{-2} s^{-1}) and 8 WAS (6.762-6.929 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

In the first trial, the transpiration of the crop at 4 (7.997-8.632 mmol H_2O m^{-2} s^{-1}), 6 (8.370-8.740 mmol H_2O m^{-2} s^{-1}) and 8 WAS (7.510-8.510 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Similarly, in the second trial, the transpiration of the crop at 4, 6 and 8 WAS ranged from 9.460-9.839, 5.584-6.002 and 5.593-5.822 mmol H_2O m^{-2} s^{-1}, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop. Likewise, in the combined the transpiration of the crop at 4 (8.918-9.188 mmol H_2O m^{-2} s^{-1}), 6 (6.987-7.218 mmol H_2O m^{-2} s^{-1}) and 8 WAS (6.552-7.067 mmol H_2O m^{-2} s^{-1}) was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Table 4. 3. 9: Transpiration of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Transpiration (mmol H_2O m^{-2} s^{-1})								
	First trial			Second trial			Combined		
	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS	4WAS	6WAS	8WAS
Biochar (B) (t ha^{-1})									
0	8.101b	8.290	7.940	9.622	6.138a	5.754a	8.862b	7.212	6.847
10	8.483a	8.710	8.120	9.810	5.374b	5.571b	9.147a	7.029	6.844
SEM	0.1309	0.1480	0.2300	0.1373	0.1218	0.0463	0.0948	0.0959	0.1171
P value	0.047	0.067	0.587	0.340	<.001	0.009	0.037	0.182	0.987
Landrace (L)									
Ex-Sokoto	8.440	8.260b	7.980	9.457b	5.819	5.545b	8.948	7.042	6.762
Kaaro	8.144	8.710a	8.080	9.976a	5.693	5.780a	9.060	7.199	6.929
SEM	0.1309	0.148	0.2300	0.1373	0.1218	0.0463	0.0948	0.0959	0.1171
P value	0.120	0.044	0.776	0.012	0.470	0.001	0.408	0.250	0.319
Rock phosphate (RP) (kg P_2O_5 ha^{-1})									
0	8.086	8.400	7.510	9.822	5.834	5.593	8.954	7.115	6.552
20	8.632	8.440	7.860	9.745	6.002	5.822	9.188	7.218	6.841
40	8.454	8.370	8.230	9.460	5.604	5.614	8.957	6.987	6.921
60	7.997	8.740	8.510	9.839	5.584	5.621	8.918	7.161	7.067
SEM	0.1851	0.2090	0.3250	0.1941	0.1722	0.0654	0.1341	0.1356	0.1656
P value	0.067	0.583	0.168	0.495	0.281	0.065	0.469	0.666	0.175
Interactions									
B X L	0.160	0.721	0.504	0.555	0.350	0.754	0.330	0.382	0.550
B X RP	0.698	0.258	0.262	0.983	0.208	0.121	0.954	0.003	0.042
L X RP	0.118	0.687	0.450	0.834	0.212	0.405	0.735	0.325	0.291
BX L X RP	0.401	0.492	0.250	0.841	0.104	0.501	0.170	0.092	0.303

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

Interactions

Significant ($P<0.05$) interaction between the biochar and rock phosphate levels on the transpiration of the crop was observed at 6 (Figure 4.3.1) and 8 (Figure 4.3.2) WAS in the combined. At 6 WAS, in the plots where no biochar was applied, 0 kg P_2O_5 ha^{-1} recorded transpiration of 7.492 mmol H_2O m^{-2} s^{-1} which was not significantly ($P>0.05$) different from 7.095-7.441 mmol H_2O m^{-2} s^{-1} recorded at the application of 20 and 40 kg P_2O_5 ha^{-1}. Application of 60 kg P_2O_5 ha^{-1} recorded transpiration of 6.819 mmol H_2O m^{-2} s^{-1} that was significantly ($P<0.05$) lower than 7.441-7.492 mmol H_2O m^{-2} s^{-1} recorded at the application of 0-20 kg P_2O_5 ha^{-1} but similar to 7.095 mmol H_2O m^{-2} s^{-1} recorded at the application of 40 kg P_2O_5 ha^{-1}. In the plots where biochar was applied, application of 60 kg P_2O_5 ha^{-1} along with the biochar was significantly ($P<0.05$) higher (7.502 mmol H_2O m^{-2} s^{-1}) in transpiration than other treatments which recorded 6.739-6.995 mmol H_2O m^{-2} s^{-1}. At 8 WAS, application of rock phosphate (20-60 kg P_2O_5 ha^{-1}) in the no biochar treatments recorded plant transpiration of 6.434-7.156 mmol H_2O m^{-2} s^{-1} that was not significantly ($P>0.05$) different from 6.673 mmol H_2O m^{-2} s^{-1} recorded where no rock phosphate was applied. However, in the biochar treatments, application of rock phosphate at 20 kg P_2O_5 ha^{-1} along with the biochar significantly ($P<0.05$) increased the plant transpiration from 6.432 mmol H_2O m^{-2} s^{-1} recorded in the treatments that received sole biochar application to 7.248 mmol H_2O m^{-2} s^{-1}, further increase in the rock phosphate application to 40-60 kg P_2O_5ha^{-1} recorded transpiration of 6.687-7.009 mmol H_2O m^{-2} s^{-1} that was not significantly ($P>0.05$) different from 6.434-7.156 mmol H_2O m^{-2} s^{-1} recorded in the no biochar treatments and 6.432 mmol H_2O m^{-2} s^{-1} recorded in the biochar treatments without rock phosphate application.

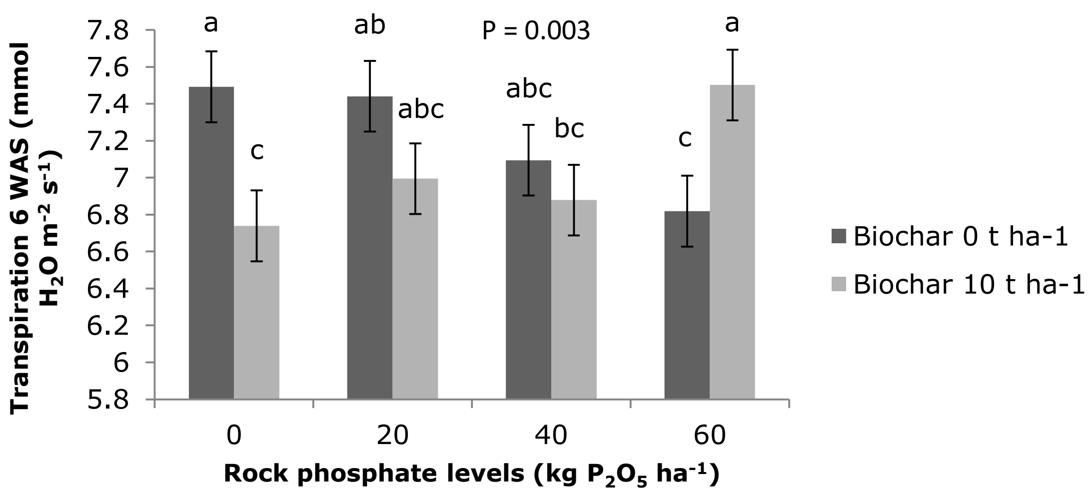

Figure 4. 3. 1: Transpiration of Bambara groundnut at 6 WAS in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

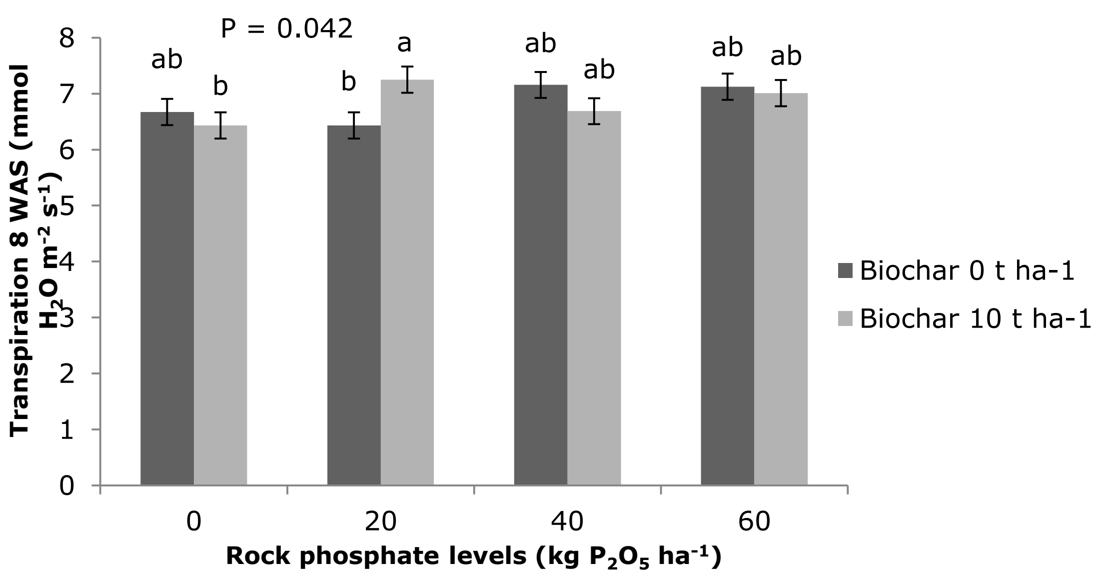

Figure 4. 3. 2: Transpiration of Bambara groundnut at 8 WAS in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.10 Number of pods per plant

Number of pods per plant of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.10.

Effect of biochar

The number of pods per plant recorded in the biochar treatment in the first trial (6-7), second trial (28-33) and the combined (17-20) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in the number of pods per plant was observed in the first trial, second trial and the combined. Ex-Sokoto landrace was significantly ($P<0.05$) higher in number of pods per plant in the first trial (9), second trial (38) and the combined (23) than Kaaro landrace which recorded 4, 23 and 14 pods per plant, respectively.

Effect of rock phosphate

The number of pods per plant recorded in the rock phosphate treatments ranged from 6-7, 26-34 and 16-20 pods in the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interactions

No significant ($P>0.05$) interaction between the treatments on the number of pods per plant was observed during the trials.

Table 4. 3. 10: Number of pods per plant of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Number of pods per plant		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	6	28	17
10	7	33	20
SEM	0.596	2.01	1.046
P value	0.149	0.123	0.057
Landrace (L)			
Ex-Sokoto	9a	38a	23a
Kaaro	4b	23b	14b
SEM	0.596	2.01	1.046
P value	<.001	<.001	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	7	34	20
20	6	26	16
40	6	30	18
60	7	31	20
SEM	0.843	2.84	1.479
P value	0.598	0.281	0.210
Interaction P values			
B X L	0.494	0.684	0.556
B X RP	0.095	0.076	0.106
L X RP	0.865	0.915	0.835
B X L X RP	0.363	0.852	0.778

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.11 Pod yield

Pod yield of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.11.

Effect of biochar

Significant (P<0.05) effect of biochar application on the pod yield of the crop was observed in the combined. Application of biochar significantly (P<0.05) increased the pod yield of the crop in the combined from 1407 kg ha^{-1} recorded where no biochar was applied to 1641 kg ha^{-1}. However, the pod yield of the crop in the first (430-524) and second trial (2383-2758 kg ha^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

Significant (P<0.05) difference between the landraces in pod yield of the crop was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded pod yield of 605, 2828 and 1717 kg ha^{-1} in the first, second and the combined, respectively that was significantly (P<0.05) higher than 348, 2313 and 1330 kg ha^{-1}, respectively recorded by Kaaro landrace.

Effect of rock phosphate

The pod yield of the crop recorded in the rock phosphate treatments ranged from 410-555, 2356-2927 and 1403-1710 kg ha^{-1}, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Table 4. 3. 11: Pod yield of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Pod yield (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	430	2383	1407b
10	524	2758	1641a
SEM	42.7	140.7	73.5
P value	0.130	0.069	0.028
Landrace (L)			
Ex-Sokoto	605a	2828a	1717a
Kaaro	348b	2313b	1330b
SEM	42.7	140.7	73.5
P value	<.001	0.015	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	492	2927	1710
20	450	2356	1403
40	410	2456	1433
60	555	2543	1549
SEM	60.4	199.0	104.0
P value	0.380	0.217	0.159
Interaction P values			
B X L	0.610	0.687	0.592
B X RP	0.176	0.012	0.008
L X RP	0.817	0.896	0.860
B X L X RP	0.132	0.624	0.734

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

Interactions

Significant ($P<.005$) interaction between the biochar and the rock phosphate levels on the pod yield of the crop was observed in the second trial (Figure 4.3.3) and the combined (Figure 4.3.4). In the second trial, the interaction revealed pod yield of 2170-3683 kg ha^{-1} and was significantly ($P<0.05$) higher (3683 kg ha^{-1}) in the treatments which received sole biochar application of 10 t ha^{-1} without the rock phosphate than other treatments (2170-2770 kg ha^{-1}). The effect of rock phosphate application was not observed in the treatments without biochar application. However, in the biochar applied plots the pod yield was decreased from 3683 kg ha^{-1} recorded in the sole biochar applied plots to 2315-2520 kg ha^{-1} recorded in the plots receiving both biochar and rock phosphate levels. In the combined, the pod yield of the crop in the interaction ranged from 1286-2134 kg ha^{-1} and was significantly ($P<0.05$) higher (2134 kg ha^{-1}) in the treatments that received sole application of 10 t ha^{-1} of biochar than in the plots which received either sole application of rock phosphate or combination of both biochar and rock phosphate (1286-1627 kg ha^{-1}).

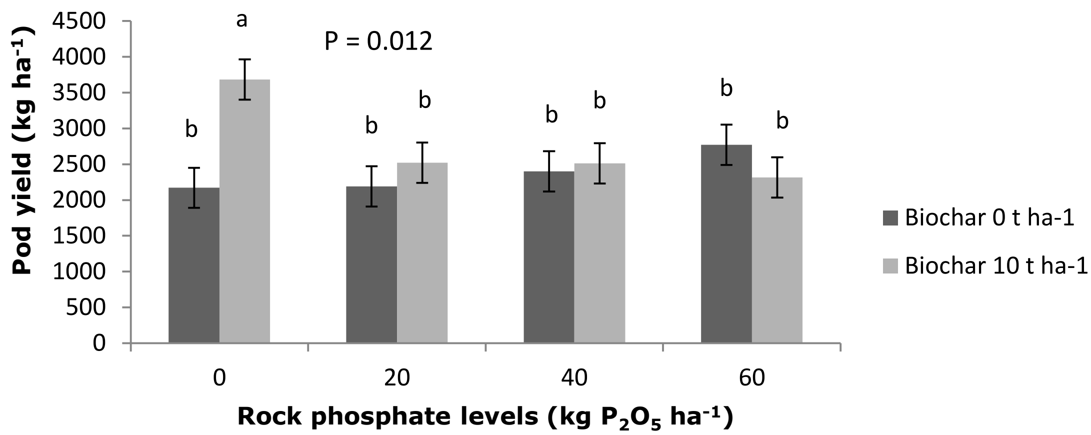

Figure 4. 3. 3: Pod yield of Bambara groundnut in the second trial as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

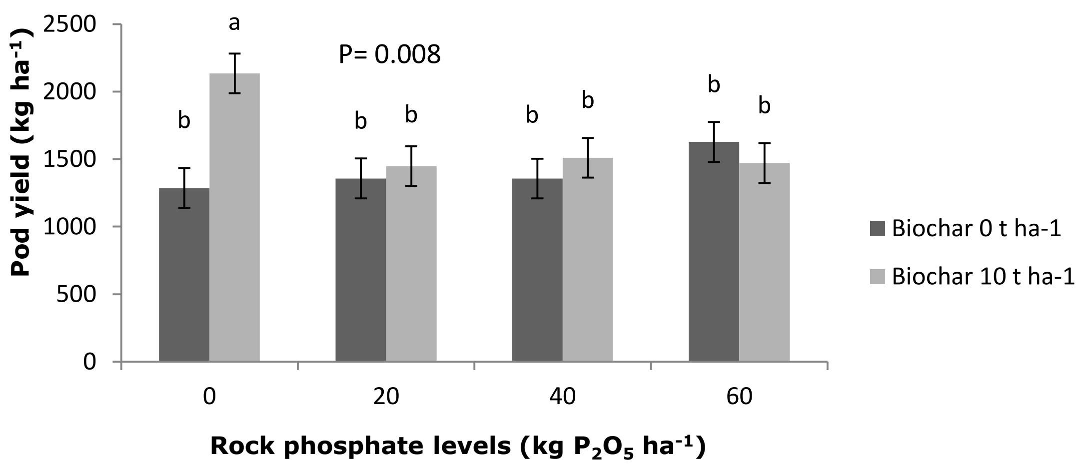

Figure 4. 3. 4: Pod yield of Bambara groundnut in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.12 Grain yield

Grain yield of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.12.

Effect of biochar

Significant (P<0.05) effect of biochar application on the grain yield of the crop was observed in the combined. Application of biochar significantly (P<0.05) increased the grain yield of the crop in the combined from 979 kg ha^{-1} recorded where no biochar was applied to 1132 kg ha^{-1}. However, the grain yield of the crop recorded in the first (289-340 ha^{-1}) and second trial (1669-1923 kg ha^{-1}) was not significantly (P>0.05) influenced by the application on biochar on the crop.

Effect of landrace

Significant (P<0.05) difference between the landraces in the grain yield was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded grain yield of 409, 2031 and 1220 kg ha^{-1} in the first trial, second trial and the combined, respectively that was significantly (P<0.05) higher than 220, 1561 and 891 kg ha^{-1}, respectively recorded by Kaaro landrace.

Effect of rock phosphate

The grain yield of the crop in the rock phosphate treatments ranged from 271-365, 1646-2069 and 973-1196 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

Significant (P<0.05) interaction between the biochar and rock phosphate levels on the grain yield of the crop was observed in the second (Figure 4.3.5) trial and the combined (Figure 4.3.6). The treatments which received sole application of 10 t ha^{-1} of biochar without the rock phosphate recorded grain yield of 2607 and 1493 kg ha^{-1} for the second trial and the combined, respectively that was significantly ($P<0.05$) higher than 1531-1922 and 899-1123 kg ha^{-1}, respectively recorded in the other treatments. In the overall, no significant ($P>0.05$) difference in the grain yield of the crop was observed as a result of sole rock phosphate application (0-60 kg P_2O_5 ha^{-1}).

Table 4. 3. 12: Grain yield of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Grain yield (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	289	1669	979b
10	340	1923	1132a
SEM	29.5	98.0	51.2
P value	0.227	0.076	0.039
Landrace (L)			
Ex-Sokoto	409a	2031a	1220a
Kaaro	220b	1561b	891b
SEM	29.5	98.0	51.2
P value	<.001	0.002	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	323	2069	1196
20	300	1646	973
40	271	1708	989
60	365	1761	1063
SEM	41.7	138.6	72.4
P value	0.451	0.161	0.128
Interaction P values			
B X L	0.757	0.703	0.648
B X RP	0.184	0.010	0.006
L X RP	0.857	0.921	0.869
B X L X RP	0.118	0.590	0.738

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

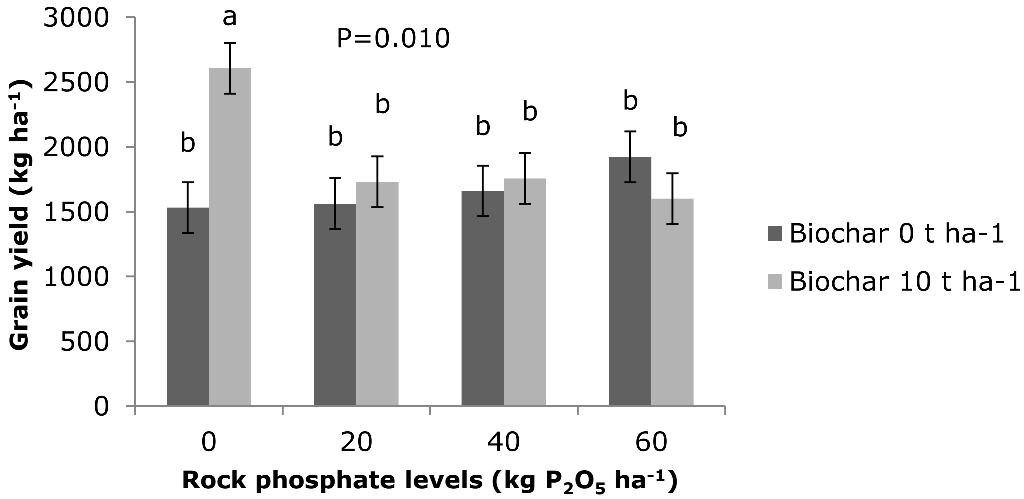

Figure 4. 3. 5: Grain yield of Bambara groundnut in the second trial as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

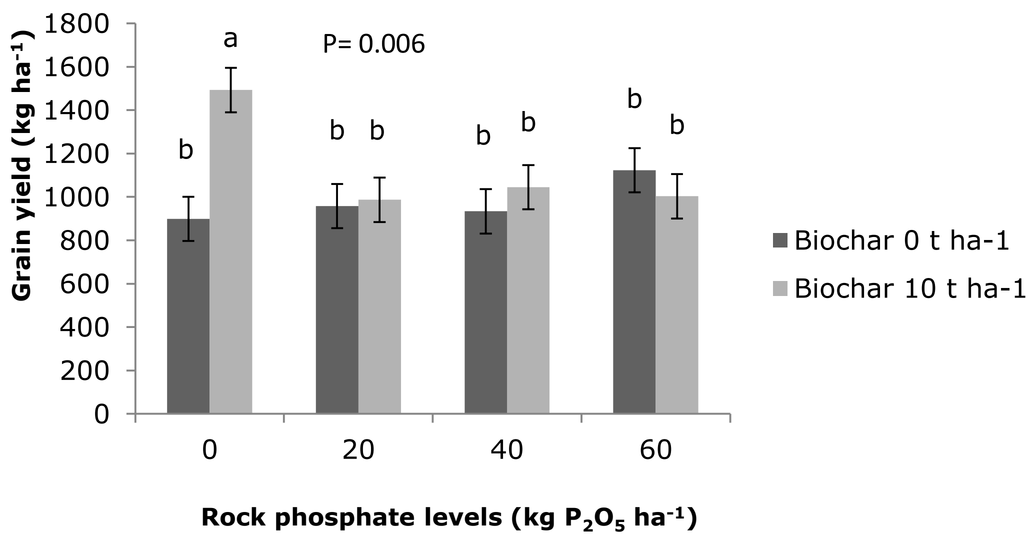

Figure 4. 3. 6: Grain yield of Bambara groundnut in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.13 Shell weight

Shell weight of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.13.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the shell weight of the crop was observed in the first trial and the combined. Application of biochar significantly ($P<0.05$) increased the shell weight of the crop from 141 and 427 kg ha^{-1} recorded in the treatments where biochar was not applied in the first trial and the combined, respectively to 183 and 509 kg ha^{-1}, respectively. However, the shell weight of the crop in the second trial (714-835 kg ha^{-1}) was not significantly influenced by the application of biochar on the crop.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in shell weight of the crop was observed in the first trial. In the first trial, Ex-Sokoto landrace recorded shell weight of 196 kg ha^{-1} which was significantly ($P<0.05$) higher than 128 kg ha^{-1} recorded by Kaaro landrace. However, the shell weight of the crop in the second trial (752-797 kg ha^{-1}) and the combined (440-497 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The shell weight of the crop in the rock phosphate treatments ranged from 139-190, 711-858 and 430-514 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Table 4. 3. 13: Shell weight of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Shell weight (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	141b	714	427b
10	183a	835	509a
SEM	13.66	45.1	23.6
P value	0.035	0.068	0.017
Landrace (L)			
Ex-Sokoto	196a	797	497
Kaaro	128b	752	440
SEM	13.66	45.1	23.6
P value	0.001	0.480	0.092
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	170	858	514
20	150	711	430
40	139	748	440
60	190	782	486
SEM	19.32	63.8	33.3
P value	0.266	0.424	0.273
Interaction P values			
B X L	0.357	0.669	0.496
B X RP	0.177	0.024	0.023
L X RP	0.631	0.836	0.860
B X L X RP	0.177	0.694	0.734

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

Interaction

Significant ($P<0.05$) interaction between the biochar and the rock phosphate levels on the shell weight of the crop was observed in the second trial (Figure 4.3.7) and the combined (Figure 4.3.8). The shell weight in the interaction ranged from 631-1076 and 386-641 kg ha^{-1} for the second trial and the combined, respectively. Application of 10 t ha^{-1} alone recorded shell weight of 1076 and 641 kg ha^{-1} for the second trial and the combined, respectively and was higher than the shell weight of 631-849 and 386-504 kg ha^{-1}, respectively recorded by the other treatments. However, in the second trial, the shell weight (1076 kg ha^{-1}) in the sole biochar treatment was comparable to 849 kg ha^{-1} obtained in the treatments that received sole application of rock phosphate at 60 kg P_2O_5 ha^{-1}.

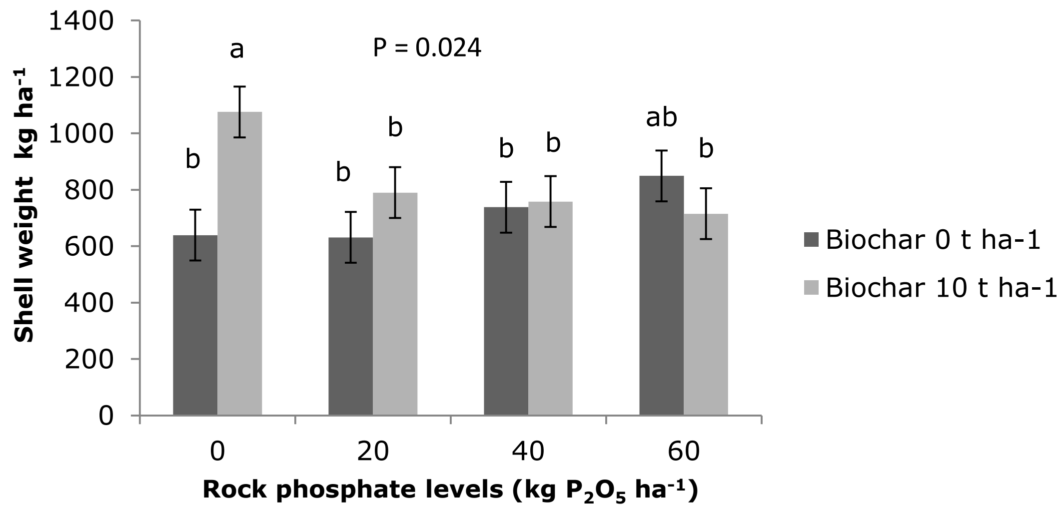

Figure 4. 3. 7: Shell weight of Bambara groundnut in the second trial as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

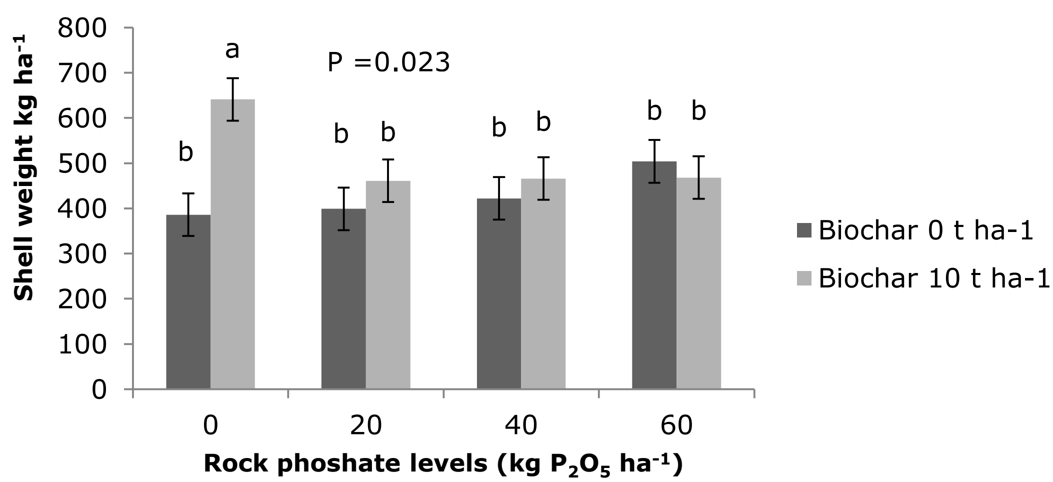

Figure 4. 3. 8: shell weight of Bambara groundnut in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.14 Shelling percentage

Shelling percentage of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.14.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the shelling percentage of the crop was observed in the first trial and the combined. In the first trial and the combined, application of biochar significantly ($P<0.05$) decreased the shelling percentage of the crop from 66.3 and 68.2 %, respectively recorded where no biochar was applied to 64.4 and 66.9 %, respectively. However, in the second trial, the shelling percentage (69.3-70.1 %) of the crop was not significantly ($P>0.05$) influenced by the application of biochar.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in shelling percentage was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded shelling percentage of 67.6, 71.9 and 69.7 % in the first trial, second trial and the combined, respectively which was significantly ($P<0.05$) higher than 63.1, 67.5 and 65.3 %, respectively recorded by Kaaro landrace

Effect of rock phosphate

The shelling percentage of the crop in the rock phosphate treatments ranged from 65.3-65.4, 69.0-70.7 and 67.1-68.0 % for the first trial, second trial and the combined and was not significantly ($P<0.05$) influenced by the application of rock phosphate on the crop.

Table 4. 3. 14: Shelling percentage of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Shelling percentage (%)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	66.3a	70.1	68.2a
10	64.4b	69.3	66.9b
SEM	0.532	0.483	0.360
P value	0.018	0.285	0.012
Landrace (L)			
Ex-Sokoto	67.6a	71.9a	69.7a
Kaaro	63.1b	67.5b	65.3b
SEM	0.532	0.483	0.360
P value	<.001	<.001	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	65.4	70.7	68.0
20	65.3	69.8	67.6
40	65.3	69.3	67.3
60	65.3	69.0	67.1
SEM	0.753	0.684	0.508
P value	0.986	0.355	0.650
Interaction P values			
B X L	0.311	0.455	0.209
B X RP	0.993	0.191	0.613
L X RP	0.015	0.797	0.250
B X L X RP	0.270	0.135	0.866

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

Interaction

Significant ($P<0.05$) interaction between the landraces and rock phosphate application on the shelling percentage of the crop was observed in the first trial (Figure 4.3.9). Application of rock phosphate at 20 and 40 kg P_2O_5 ha^{-1} on Ex-Sokoto landrace recorded shelling percentage of 67.9-69.6 % which was significantly higher than 61.0-64.3 % recorded by Kaaro landrace irrespective of the P_2O_5 levels. However, no significant ($P>0.05$) difference among the rock phosphate levels on Kaaro landrace was observed. Similarly, the difference between the landraces at 0 and 60 kg P_2O_5 ha^{-1} was not observed.

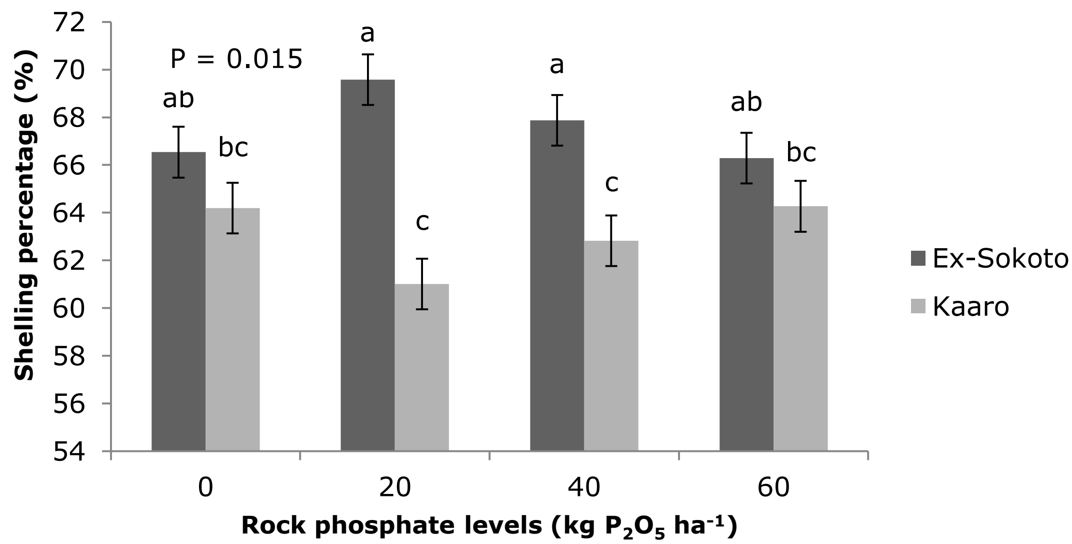

Figure 4. 3. 9: Shelling percentage of Bambara groundnut in the first trial as influenced by landrace and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.15 Harvest index

Harvest index of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.15.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the harvest index of the crop was observed in the second trial and the combined. In the second trial and the combined, application of biochar on the crop significantly ($P<0.05$) decreased the harvest index of the crop from 33.8 and 21.4 %, respectively recorded where no biochar was applied to 30.8 and 19.5 %, respectively. However, in the first year, the harvest index of the crop (8.2-9.0 %) was not significantly influenced by the application of biochar on the crop.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in the harvest index was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded harvest index of 10.9, 35.5 and 23.2 % in the first trial, second trial and the combined, respectively which was significantly ($P<0.05$) higher than 6.3, 29.1 and 17.7 %, respectively recorded by Kaaro landrace.

Effect of rock phosphate

Significant ($P<0.05$) effect of rock phosphate application on the harvest index of the crop was observed in the second trial and the combined. In the second trial and the combined, application of rock phosphate (20-60 kg P_2O_5 ha^{-1}) significantly ($P<0.05$) decreased the harvest index of the crop from 36.9 and 22.8 %, respectively recorded where no rock phosphate was applied to 30.2-31.2 and 19.1-20.4 %, respectively.

However, in the first trial, the harvest index of the crop (7.3-9.6 %) and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the harvest index of the crop was observed during the trials.

Table 4. 3. 15: Harvest index of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Harvest index (%)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	9.0	33.8a	21.4a
10	8.2	30.8b	19.5b
SEM	0.497	1.041	0.577
P value	0.270	0.047	0.022
Landrace (L)			
Ex-Sokoto	10.9a	35.5a	23.2a
Kaaro	6.3b	29.1b	17.7b
SEM	0.497	1.041	0.577
P value	<.001	<.001	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	8.7	36.9a	22.8a
20	8.8	30.2b	19.5b
40	7.3	30.9b	19.1b
60	9.6	31.2b	20.4b
SEM	0.703	1.473	0.816
P value	0.148	0.012	0.011
Interaction P values			
B X L	0.306	0.793	0.495
B X RP	0.138	0.079	0.106
L X RP	0.239	0.438	0.797
B X L X RP	0.206	0.363	0.291

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.16 Haulm weight

Haulm weight of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.16.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the haulm weight of the crop was observed in the first trial, second trial and the combined. Application of biochar significantly ($P<0.05$) increased the haulm weight of the crop from 2791, 2675 and 2733 kg ha^{-1} recorded in the treatments where no biochar was applied in the first trial, second trial and the combined, respectively to 3489, 3461 and 3475 kg ha^{-1}, respectively.

Effect of landrace

The haulm weight of the crop recorded in the first trial (3123-3157 ha^{-1}), second trial (2936-3199 ha^{-1}) and the combined (3029-3178 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The haulm weight of the crop in the rock phosphate treatments ranged from 3113-3185, 2757-3231 and 2971-3190 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the haulm weight of the crop was observed during the trials.

Table 4. 3. 16: Haulm weight of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Haulm weight (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	2791b	2675b	2733b
10	3489a	3461a	3475a
SEM	150.0	195.6	123.2
P value	0.003	0.008	<.001
Landrace (L)			
Ex-Sokoto	3123	2936	3029
Kaaro	3157	3199	3178
SEM	150.0	195.6	123.2
P value	0.873	0.349	0.397
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	3185	2757	2971
20	3113	3141	3127
40	3114	3142	3128
60	3148	3231	3190
SEM	212.1	276.6	174.3
P value	0.994	0.629	0.834
Interaction P values			
B X L	0.255	0.928	0.382
B X RP	0.372	0.955	0.857
L X RP	0.468	0.323	0.889
B X L X RP	0.922	0.376	0.376

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.17 Stover weight (shell + haulm)

Stover weight of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.17.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the stover weight of the crop was observed in the first trial, second trial and the combined. Application of biochar significantly ($P<0.05$) increased the stover weight of the crop from 2932, 3389 and 3160 kg ha^{-1} recorded where no biochar was applied in the first trial, second trial and the combined, respectively to 3672, 4296 and 3984 kg ha^{-1}, respectively.

Effect of landrace

No significant ($P>0.05$) difference between the landraces in the stover weight of the crop was observed during the first trial, second trial and the combined. The stover weight of the landraces in the first trial (3285-3319 kg ha^{-1}), second trial (3734-3951 kg ha^{-1}) and the combined (3526-3618 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The stover weight of the crop recorded in the rock phosphate treatment ranged from 3252-3354, 3614-4012 and 3484-3676 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate.

Interaction

No significant ($P>0.05$) interaction between the treatments on the stover weight of the crop was observed during the trials.

Table 4. 3. 17: Stover weight of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Stover weight (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	2932b	3389b	3160b
10	3672a	4296a	3984a
SEM	158.7	228.4	139.1
P value	0.003	0.009	<.001
Landrace (L)			
Ex-Sokoto	3319	3734	3526
Kaaro	3285	3951	3618
SEM	158.7	228.4	139.1
P value	0.880	0.506	0.643
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	3354	3614	3484
20	3262	3852	3557
40	3252	3891	3572
60	3338	4012	3676
SEM	224.4	323.1	196.7
P value	0.983	0.849	0.922
Interaction P values			
B X L	0.248	0.787	0.374
B X RP	0.347	0.962	0.698
L X RP	0.501	0.379	0.888
B X L X RP	0.941	0.474	0.445

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.18 Total dry weight

Total dry weight of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.18.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the total dry weight of the crop was observed in the first trial, second trial and the combined. Application of biochar significantly ($P<0.05$) increased the total dry weight of the crop from 3221, 5058 and 4139 kg ha^{-1} recorded in the first trial, second trial and the combined, respectively to 4012, 6219 and 5116 kg ha^{-1}, respectively.

Effect of landrace

The total dry weight of the crop recorded by the landraces in the first trial (3505-3728 kg ha^{-1}), second trial (5512-5765 kg ha^{-1}) and the combined (4509-4746 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The total dry weight of the crop recorded in the rock phosphate treatments ranged from 3523-3703, 5498-5773 and 4530-4738 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the total dry weight of the crop was observed during the trials.

Table 4. 3. 18: Total dry weight of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Total dry weight (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	3221b	5058b	4139b
10	4012a	6219a	5116a
SEM	176.7	302.4	175.1
P value	0.004	0.011	<.001
Landrace (L)			
Ex-Sokoto	3728	5765	4746
Kaaro	3505	5512	4509
SEM	176.7	302.4	175.1
P value	0.380	0.559	0.341
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	3677	5683	4680
20	3562	5498	4530
40	3523	5599	4561
60	3703	5773	4738
SEM	249.9	427.7	247.7
P value	0.946	0.973	0.924
Interaction P values			
B X L	0.276	0.743	0.401
B X RP	0.291	0.550	0.277
L X RP	0.619	0.503	0.879
B X L X RP	0.894	0.658	0.588

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.19 1000-grain weight

1000 grain weight of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.19.

Effect of landrace

The 1000-grain weight of the crop in the biochar treatments ranged from 507.0-519.0, 701.5-715.9 and 610.3-611.6 g for the first trial, second trial and the combined and was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

Significant (P<0.05) difference between the landraces in 1000-grain weight was observed in the second trial and the combined. In the second trial and the combined, Kaaro landrace recorded 1000-grain weight of 791.9 and 665.2 g, respectively which was significantly (P<0.05) higher than 626.0 and 556.7 g, respectively recorded by Ex-Sokoto landrace. However, in the first trial, the 1000-grain weight of the landraces ranged from 487-539 g and was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

The 1000-grain weight of the crop in the rock phosphate treatments ranged from 499.0-533.0, 688.0-735.4 and 601.2-624.8 g for the first trial, second trial and the combined, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the 1000 grain weight of the crop was observed during the trials.

Table 4. 3. 19: 1000-grain weight of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	1000-grain weight		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	519	701.5	610.3
10	507	715.9	611.6
SEM	20.0	13.47	12.04
P value	0.677	0.455	0.941
Landrace (L)			
Ex-Sokoto	487	626.0b	556.7b
Kaaro	539	791.3a	665.2a
SEM	20.0	13.47	12.04
P value	0.076	<.001	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	514	735.4	624.8
20	507	695.8	601.2
40	499	715.4	607.1
60	533	688.0	610.7
SEM	28.2	19.05	17.03
P value	0.843	0.312	0.792
Interaction P values			
B X L	0.480	0.993	0.558
B X RP	0.749	0.069	0.526
L X RP	0.649	0.079	0.139
B X L X RP	0.592	0.390	0.715

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.20 Grain N concentration

Grain N concentration of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.20.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the grain N concentration of the crop was observed in the first trial. Application of biochar in the first trial increased the grain N concentration of the crop from 3.31 % recorded where no biochar was applied to 3.56 %. However, the grain N concentration of the crop in the second trial (3.19-3.20) and the combined (3.25-3.36 %) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in grain N concentration was observed in the second trial and was higher (3.28 %) in Kaaro landrace than Ex-Sokoto landrace (3.11 %). However, for the first trial and the combined, the grain N concentration ranged from 3.40-3.44 and 3.25-3.36 %, respectively and was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

Significant ($P<0.05$) effect of rock phosphate application on the grain N concentration of the crop was observed in the second trial. Application of 20 kg P_2O_5 ha^{-1} on the crop increased the grain N concentration from 3.11 % recorded where no rock phosphate was applied to 3.36 %. Further increase in the rock phosphate application to 40 kg P_2O_5 ha^{-1}, decreased the grain N concentration to 3.10 % which was not significantly ($P>0.05$) different from 3.11 % recorded in the treatments where no rock phosphate was applied, and 3.21 % recorded in the treatments that received rock phosphate application of 60 kg P_2O_5 ha^{-1}. Similarly, no significant (P>0.05) difference in grain N concentration between the treatments that received application of 20 and 60 kg P_2O_5 ha^{-1} was observed. Hence, application of 20 kg P_2O_5 ha^{-1} was optimum. However, in the first trial and the combined, the grain N concentration of the crop ranged from 3.35-3.56 and 3.23-3.38 %, respectively and was not significantly (P>0.05) different between the rock phosphate levels.

Interaction

Significant (P<0.05) interaction between the biochar levels and the landraces on the grain N concentration of the crop was observed in the first trial (Figure 4.3.10) and the combined (Figure 4.3.11).

In the first trial, application of 10 t ha^{-1} of biochar significantly (P<0.05) increased the grain N concentration of Ex-Sokoto landrace from 3.16 % recorded where no biochar was applied to 3.64 %. However, for Kaaro landrace, application of 10 t ha^{-1} of biochar recorded grain N concentration of 3.42 % which was not significantly (P>0.05) different from 3.46 % recorded in the treatments where no biochar was applied on the same landrace. Overall, the grain N concentration (3.64 %) recorded by Ex-Sokoto landrace in the treatments where 10 t ha^{-1} of biochar was applied was not significantly (P>0.05) different from 3.42 and 3.46 % recorded by the application of 0 and 10 t ha^{-1}, respectively on Kaaro landrace.

In the combined, application of 10 t ha^{-1} of biochar increased the grain N concentration of Ex-Sokoto landrace from 3.13 % recorded where no biochar was applied to 3.38 %. However, for Kaaro landrace, application of 10 t ha^{-1} of biochar recorded grain N concentration of 3.34 % which was not significantly (P>0.05) different from 3.38 % recorded in the treatments where no biochar was applied on the same landrace. Overall, the grain N concentration (3.38 %) in the treatments where 10 t ha^{-1} of biochar was applied on Ex-Sokoto landrace was not significantly ($P>0.05$) different from 3.34 and 3.38 % recorded by the application of 0 and 10 t ha^{-1}, respectively on Kaaro landrace. Furthermore, the grain N concentration recorded in the treatments that received no biochar application on Ex-Sokoto landrace was lower (3.13 %) than the N concentration (3.34-3.38 %) recorded by other treatments irrespective of the landrace.

Table 4. 3. 20: Grain N concentration of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Grain N concentration (%)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	3.31b	3.20	3.25
10	3.53a	3.19	3.36
SEM	0.064	0.039	0.037
P value	0.021	0.836	0.054
Landrace (L)			
Ex-Sokoto	3.40	3.11b	3.25
Kaaro	3.44	3.28a	3.36
SEM	0.064	0.039	0.037
P value	0.669	0.004	0.051
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	3.40	3.11b	3.25
20	3.37	3.36a	3.36
40	3.35	3.10b	3.23
60	3.56	3.21ab	3.38
SEM	0.090	0.055	0.053
P value	0.377	0.008	0.092
Interaction P values			
B X L	0.008	0.534	0.008
B X RP	0.666	0.798	0.863
L X RP	0.087	0.348	0.123
B X L X RP	0.557	0.989	0.692

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

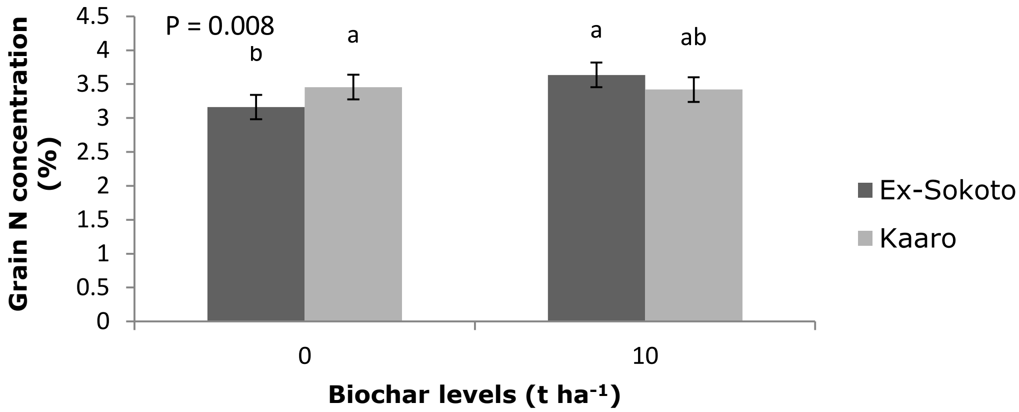

Figure 4. 3. 10: Grain N concentration of Bambara groundnut in the first trial as influenced by landrace and biochar application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

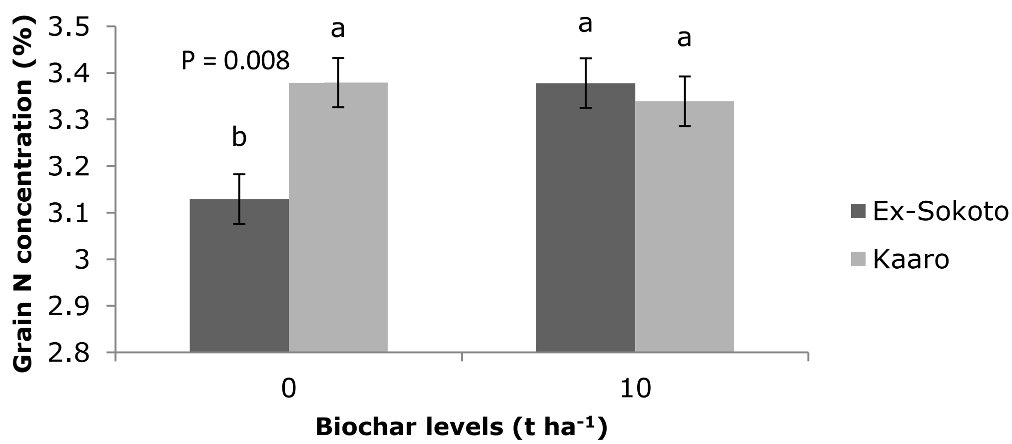

Figure 4. 3. 11: Grain N concentration of Bambara groundnut in the combined as influenced by landrace and biochar application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.21 Stover N concentration

Stover N concentration of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.21.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the stover N concentration of the crop was observed in the first trial. Application of biochar on the crop significantly ($P<0.05$) decreased the stover N concentration from 2.71 % recorded in the treatments where no biochar was applied to 2.57 %. However, the stover N concentration recorded in the biochar treatments in the second trial (2.92-3.00 %) and the combined (2.72-2.82 %) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

The stover N concentration recorded by the landraces in the first trial (2.64-2.65 %), second trial (2.92-3.02 %) and the combined (2.77-2.83 %) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The stover N concentration of the crop in the rock phosphate treatments ranged from 2.60-2.68, 2.91-3.03 and 2.77-2.85 %, respectively for the first trial, second trial and the combined and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interactions

No significant ($P>0.05$) interaction between the treatments on the stover N concentration of the crop was observed during the trials.

Table 4. 3. 21: Stover N concentration of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Stover N concentration (%)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	2.71a	2.92	2.82
10	2.57b	3.00	2.78
SEM	0.042	0.045	0.031
P value	0.023	0.264	0.401
Landrace (L)			
Ex-Sokoto	2.64	3.02	2.83
Kaaro	2.65	2.92	2.77
SEM	0.042	0.045	0.031
P value	0.859	0.066	0.217
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	2.60	2.98	2.79
20	2.63	2.91	2.77
40	2.66	3.03	2.85
60	2.68	2.92	2.80
SEM	0.061	0.063	0.044
P value	0.799	0.474	0.598
Interaction P values			
B X L	0.482	0.611	0.901
B X RP	0.532	0.534	0.237
L X RP	0.350	0.277	0.112
B X L X RP	0.140	0.253	0.119

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.22 Grain N content

Grain N content of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.22.

Effect of biochar

The grain N content of the crop in the first (9.4-12.2 kg ha^{-1}) and second trial (52.8-60.7 kg ha^{-1}) in the biochar treatments was not significantly (P>0.05) influenced by the application of biochar on the crop. However, in the combined, application of biochar significantly (P<0.05) increased the grain N content of the crop from 31.1 kg ha^{-1} recorded where no biochar was applied to 36.5 kg ha^{-1}.

Effect of landrace

Significant (P<0.05) difference between the landraces in grain N content was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded grain N content of 14.1, 62.5 and 38.3 kg ha^{-1} in the first trial, second trial and the combined, respectively and was higher than Kaaro landrace which recorded 7.5, 51.0 and 29.3 kg ha^{-1}, respectively.

Effect of rock phosphate

The grain N content of the crop recorded in the rock phosphate treatments ranged from 9.3-12.7, 52.4-63.8 and 30.8-37.6 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Table 4. 3. 22: Grain N content of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Grain N content (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	9.4	52.8	31.1b
10	12.2	60.7	36.5a
SEM	1.113	2.88	1.54
P value	0.077	0.063	0.017
Landrace (L)			
Ex-Sokoto	14.1a	62.5a	38.3a
Kaaro	7.5b	51.0b	29.3b
SEM	1.113	2.88	1.54
P value	<.001	0.008	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	11.3	63.8	37.6
20	9.9	54.5	32.2
40	9.3	52.4	30.8
60	12.7	56.3	34.5
SEM	1.573	4.07	2.18
P value	0.433	0.234	0.152
Interaction P values			
B X L	0.288	0.611	0.388
B X RP	0.259	0.006	0.004
L X RP	0.687	0.931	0.886
B X L X RP	0.199	0.531	0.728

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

Interaction

Significant ($P<0.05$) interaction between the biochar and the rock phosphate levels on the grain N content of the crop was observed in the second trial (Figure 4.3.12) and the combined (Figure 4.3.13). In both the second trial and the combined, application of rock phosphate in the treatments where no biochar was applied did not significantly ($P<0.05$) influence the grain N content of the crop. However, for the treatments where biochar was applied, additional application of rock phosphate significantly ($P<0.05$) decreased the grain N content of the crop from 80.4 and 47.2 kg ha^{-1} recorded in the sole biochar treatments in the second trial and the combined, respectively to 51.4-57.9 and 32.6-33.2 kg ha^{-1}, respectively. The difference among the treatments that received combination of biochar and rock phosphate application, and that which received rock phosphate alone without biochar or those treatments without either biochar or rock phosphate application was not observed. Overall, the sole biochar treatment was significantly ($P<0.05$) higher than other treatments in both the second trial and the combined.

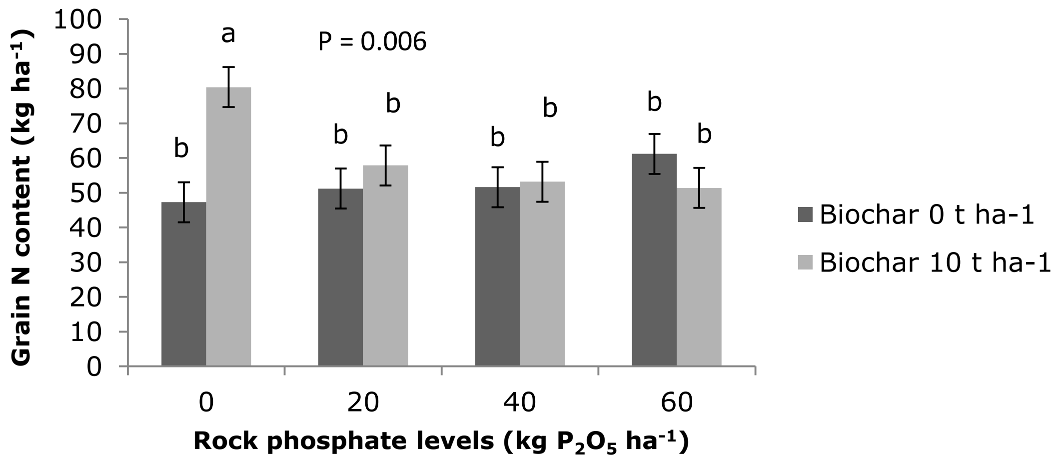

Figure 4. 3. 12: Grain N content of Bambara groundnut in the second trial as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

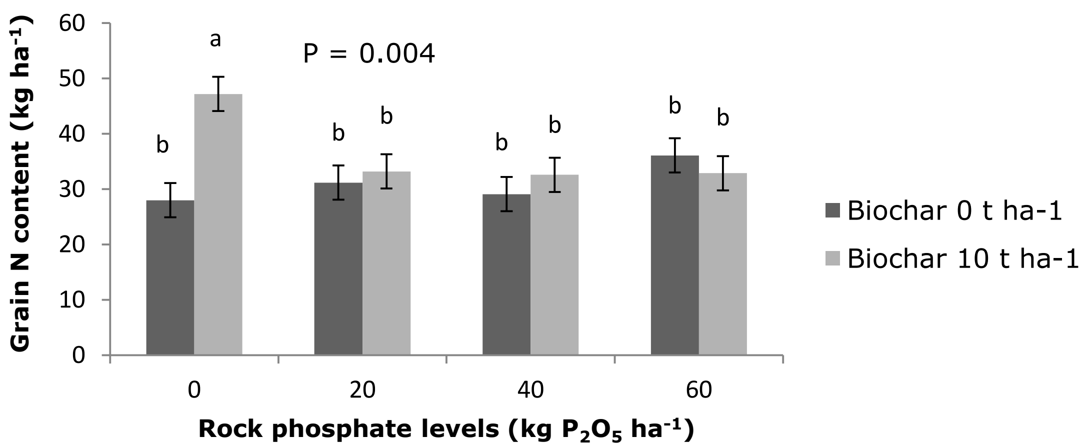

Figure 4. 3. 13: Grain N content of Bambara groundnut in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.23 Stover N content

Stover N content of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.23.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the stover N content of the crop was observed in the first trial, second trial and the combined. Application of biochar increased the stover N content of the crop from 80.0, 97.8 and 88.9 kg ha^{-1} recorded where no biochar was applied in the first trial, second trial and the combined, respectively to 93.9, 128.4 and 111.2 kg ha^{-1}, respectively.

Effect of landrace

The stover N content of the landraces in the first trial (86.7-87.1 kg ha^{-1}), second trial (112.2-114.1 kg ha^{-1}) and the combined (99.7-100.4 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The stover N content of the crop recorded in the rock phosphate treatments ranged from 85.4-90.0, 106.3-117.5 and 96.3-103.3 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the stover N content of the crop was observed during the trials.

Table 4. 3. 23: Stover N content of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Stover N content (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	80.0b	97.8b	88.9b
10	93.9a	128.4a	111.2a
SEM	4.26	7.20	4.18
P value	0.028	0.005	<.001
Landrace (L)			
Ex-Sokoto	87.1	112.2	99.7
Kaaro	86.7	114.1	100.4
SEM	4.26	7.20	4.18
P value	0.950	0.855	0.900
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	86.4	106.3	96.3
20	86.0	112.2	99.1
40	85.4	117.5	101.4
60	90.0	116.6	103.3
SEM	6.03	10.18	5.92
P value	0.947	0.859	0.855
Interaction P values			
B X L	0.181	0.829	0.380
B X RP	0.556	0.950	0.884
L X RP	0.258	0.559	0.925
B X L X RP	0.892	0.735	0.734

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.24 Total N content

Total N content of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.24.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the total N content of the crop was observed in the first trial, second trial and the combined. Application of biochar significantly ($P<0.05$) increased the total N content of the crop from 89.3, 150.7 and 120.0 kg ha^{-1} recorded where no biochar was applied in the first trial, second trial and the combined, respectively to 106.1, 189.1 and 147.6 kg ha^{-1}, respectively

Effect of landrace

The total N content of the landraces in the first trial (94.3-101.2 kg ha^{-1}), second trial (165.1-174.7 kg ha^{-1}) and the combined (129.7-138.0 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces

Effect of rock phosphate

The total N content of the crop recorded in the rock phosphate treatments ranged from 94.7-102.7, 166.8-172.9 and 131.3-137.8 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the total N content of the crop was observed during the trials.

Table 4. 3. 24: Total N content of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Total N content (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	89.3b	150.7b	120.0b
10	106.1a	189.1a	147.6a
SEM	4.88	9.45	5.32
P value	0.021	0.007	<.001
Landrace (L)			
Ex-Sokoto	101.2	174.7	138.0
Kaaro	94.3	165.1	129.7
SEM	4.88	9.45	5.32
P value	0.326	0.474	0.275
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	97.7	170.1	133.9
20	95.8	166.8	131.3
40	94.7	169.8	132.2
60	102.7	172.9	137.8
SEM	6.90	13.36	7.52
P value	0.849	0.991	0.932
Interaction P values			
B X L	0.160	0.749	0.347
B X RP	0.436	0.598	0.441
L X RP	0.405	0.668	0.934
B X L X RP	0.973	0.847	0.794

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.25 Nitrogen harvest index

Nitrogen harvest index of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.25.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the N harvest index of the crop was observed in the second trial and the combined. Application of biochar significantly ($P<0.05$) decreased the N harvest index of the crop in the second trial and the combined from 35.78 and 23.25 % recorded where no biochar was applied in the second trial and the combined, respectively to 32.01 and 21.52 %, respectively. However, the N harvest index of the crop recorded in the first trial (10.72-11.04 %) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

Significant ($P<0.05$) difference between the landraces in N harvest index of the crop was observed in the first trial, second trial and the combined. Ex-Sokoto landrace recorded significantly ($P>0.05$) higher N harvest index of 13.68, 36.14 and 24.91 % for the first trial, second trial and the combined, respectively than Kaaro landrace which recorded 8.08, 31.65 and 19.86 %, respectively.

Effect of rock phosphate

Significant ($P<0.05$) effect of rock phosphate application on the N harvest index of the crop was observed in the second trial and the combined. In the second trial, application of rock phosphate significantly ($P<0.05$) decreased the N harvest index of the crop from 37.82 % recorded where no rock phosphate was applied to 31.29-33.32 % and no significant difference between the levels (20-60 kg P_2O_5 ha^{-1}) was observed. In the combined, the N harvest index was higher in the treatments that received application of 0 and 60 kg P_2O_5 ha^{-1} (24.49 and 22.73 %, respectively) than 40 kg P_2O_5 ha^{-1} (20.19 %). Similarly, application of 20 kg P_2O_5 ha^{-1} (22.13 %) was comparable to both 0 and 60 kg P_2O_5 ha^{-1}, and also comparable to 40 kg P_2O_5 ha^{-1}. However, in the first trial, the N harvest index of the crop ranged from 9.08-12.32 % and was not significantly (P>0.05) influenced by the application of rock phosphate.

Interaction

Significant (P<0.05) interaction between the biochar and rock phosphate levels on the N harvest index of the crop was observed in the second trial (Figure 4.3.14) and the combined (Figure 4.3.15).

In the second trial, application of rock phosphate (20-60 kg P_2O_5 ha^{-1}) alone without the biochar recorded N harvest index of 33.12-37.90 % that was not significantly (P<0.05) different from 36.19 % recorded where no rock phosphate was applied. Similarly, no difference between the rock phosphate levels (20-60 kg P_2O_5 ha^{-1}) was observed. However, in the treatments where biochar was applied, application of biochar alone without the rock phosphate recorded N harvest index of 39.46 % that was significantly (P<0.05) higher than 28.39-30.71 % recorded in the treatments which received biochar along with the rock phosphate levels. In the overall, application of biochar alone recorded the highest N harvest index of 39.46 % that was not significantly (P>0.05) different from 36.19, 35.92 and 37.90 % recorded with the sole application 0, 20 and 60 kg P_2O_5 ha^{-1}, respectively in the no biochar treatments. Likewise, the least N harvest index (28.39-29.47 %) was recorded in the treatments which received 40 and 60 kg P_2O_5 ha^{-1} along with the biochar and was comparable to 30.71 and 33.12 % recorded in the treatments that received 20 kg

P_2O_5 ha^{-1} along with the biochar treatment and the treatment that received 40 kg P_2O_5 ha^{-1} without the biochar, respectively.

In the combined, application of 20 kg P_2O_5 ha^{-1} in the no biochar treatments recorded N harvest index of 24.28 % that was significantly ($P<0.05$) higher than 20.44 % recorded in the treatments that received application of 40 kg P_2O_5 ha^{-1} without the biochar but similar to 23.44 and 24.84 % recorded in the treatments applied 0 and 60 kg P_2O_5 ha^{-1}, respectively. However, in the treatments that received biochar application, application of rock phosphate (20-60 kg P_2O_5 ha^{-1}) along with the biochar decreased the N harvest index of the crop from 25.54 % recorded in the treatments that received sole biochar application to 19.94-20.63 %. However, no significant difference in the rock phosphate levels (20-60 kg P_2O_5 ha^{-1}) was observed in the plots that received both biochar and rock phosphate application. In the overall, the N harvest index of the crop (25.54 %) recorded in the sole biochar application was comparable to 23.44, 24.28 and 24.84 % recorded in the no biochar treatments which received rock application of 0, 20 and 60 kg P_2O_5 ha^{-1}, respectively.

Table 4. 3. 25: Nitrogen harvest index of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	N harvest index (%)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	10.72	35.78a	23.25a
10	11.04	32.01b	21.52b
SEM	0.606	0.949	0.58
P value	0.737	0.009	0.039
Landrace (L)			
Ex-Sokoto	13.68a	36.14a	24.91a
Kaaro	8.08b	31.65b	19.86b
SEM	0.666	0.949	0.58
P value	<.001	0.002	<.001
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	11.17	37.82a	24.49a
20	10.95	33.32b	22.13ab
40	9.08	31.29b	20.19b
60	12.32	33.15b	22.73a
SEM	0.942	1.342	0.820
P value	0.131	0.013	0.005
Interaction P values			
B X L	0.990	0.916	0.937
B X RP	0.151	0.018	0.019
L X RP	0.088	0.232	0.759
B X L X RP	0.092	0.063	0.419

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

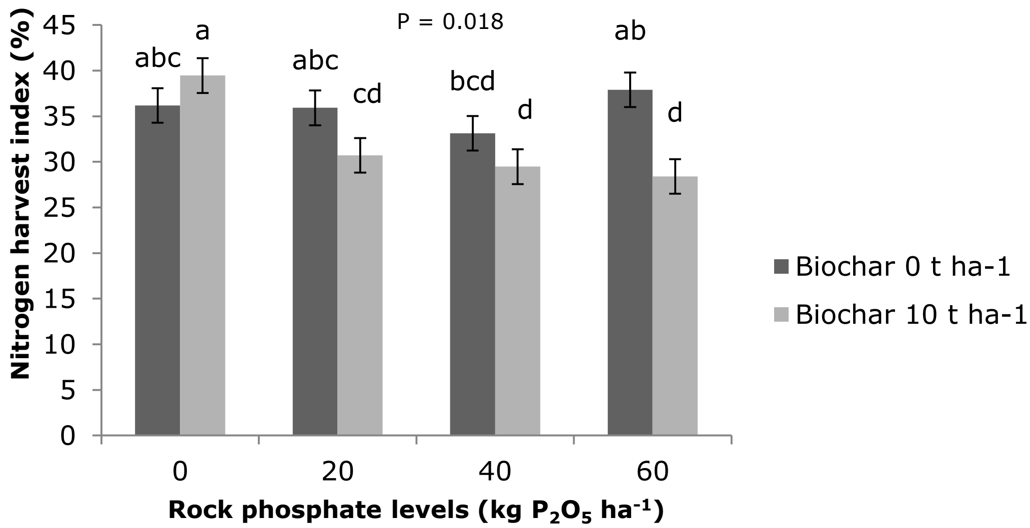

Figure 4. 3. 14: Nitrogen harvest index of Bambara groundnut in the second trial as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

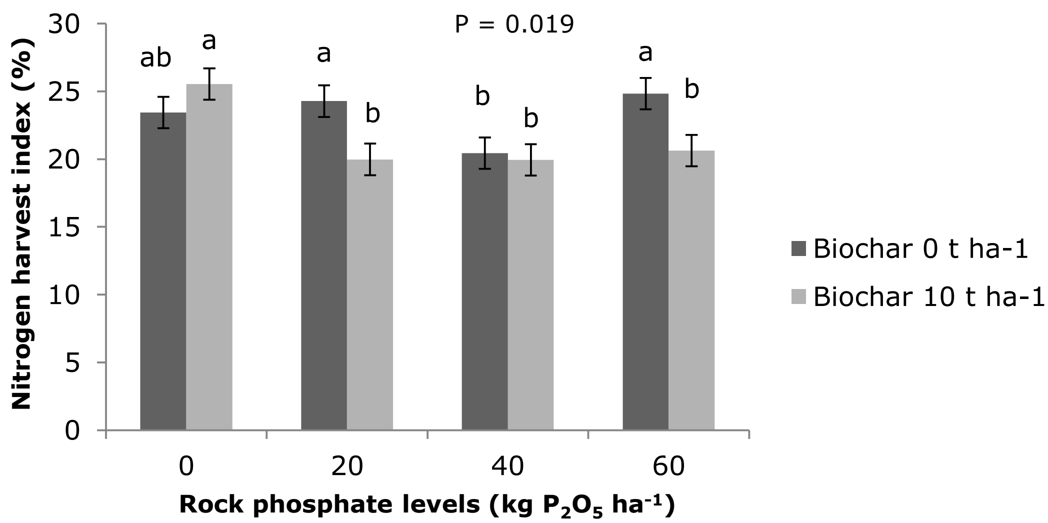

Figure 4. 3. 15: Nitrogen harvest index of Bambara groundnut in the combined as influenced by biochar and rock phosphate application at the Field Research Station of the Crops For the Future. Bars with the same letter(s) are not significantly different at 5% level using Duncan's Multiple Range Test. Error bars are standard error of mean (SEM) values.

4.3.26 Percentage N derived from the atmosphere (% ndfa)

Percentage N derived from the atmosphere of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.26.

Effect of biochar

The % ndfa of the crop in the first trial (44.4-45.6 %), second trial (56.6-61.2 %) and the combined (51.1-52.8 %) was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

The % ndfa recorded by the landraces in the first trial (43.6-46.4 %), second trial (56.5-61.3 %) and the combined (50.1-53.8 %) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

The % ndfa recorded by the crop in the rock phosphate treatments ranged from 41.5-47.7, 57.0-61.3 and 49.9-54.4 % for the first trial, second trial and the combined and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant (P>0.05) interaction between the treatments on the % ndfa of the crop was observed during the trials.

Table 4. 3. 26: Percentage N derived from the atmosphere (% ndfa) of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Percentage N derived from the atmosphere (% ndfa)		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	45.6	56.6	51.1
10	44.4	61.2	52.8
SEM	1.78	2.53	1.55
P value	0.645	0.217	0.447
Landrace (L)			
Ex-Sokoto	43.6	56.5	50.1
Kaaro	46.4	61.3	53.8
SEM	1.78	2.53	1.55
P value	0.285	0.192	0.091
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	41.5	58.4	49.9
20	47.7	57.0	52.4
40	47.4	61.3	54.4
60	43.4	58.9	51.2
SEM	2.51	3.58	2.19
P value	0.238	0.865	0.529
Interaction P values			
B X L	0.309	0.985	0.544
B X RP	0.581	0.584	0.895
L X RP	0.659	0.785	0.696
B X L X RP	0.976	0.847	0.899

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.27 Nitrogen fixed in the shoot

Nitrogen fixed in the shoot of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.27.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the N fixed in the shoot of the crop was observed in the second trial and the combined. Application of biochar significantly ($P<0.05$) increased the N fixed in the shoot of the crop from 89.0 and 64.9 kg ha^{-1} recorded in the second trial and the combined, respectively to 116.7 and 81.5 kg ha^{-1}, respectively. However, in the first trial, the N fixed in the shoot of the crop (40.9-46.3 kg ha^{-1}) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

The N fixed in the shoot of the landraces in the first trial (43.3-43.8 kg ha^{-1}), second trial (101.8-103.9 kg ha^{-1}) and the combined (72.6-73.8 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The N fixed in the shoot of the crop in the rock phosphate treatments ranged from 39.3-46.0, 97.8-106.0 and 71.3-75.1 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the N fixed in the shoot of the crop was observed during the trials.

Table 4. 3. 27: Nitrogen fixed in the shoot of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	N fixed in the shoot (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	40.9	89.0b	64.9b
10	46.3	116.7a	81.5a
SEM	2.53	7.96	4.18
P value	0.140	0.020	0.007
Landrace (L)			
Ex-Sokoto	43.3	101.8	72.6
Kaaro	43.8	103.9	73.8
SEM	2.53	7.96	4.18
P value	0.897	0.852	0.828
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	39.3	103.4	71.3
20	46.0	97.8	71.9
40	44.3	106.0	75.1
60	44.7	104.1	74.4
SEM	3.58	11.26	5.91
P value	0.574	0.961	0.961
Interaction P values			
B X L	0.108	0.982	0.633
B X RP	0.294	0.720	0.833
L X RP	0.548	0.673	0.904
B X L X RP	0.953	0.621	0.571

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.28 Total N fixed

Total N fixed of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.28.

Effect of biochar

Significant ($P<0.05$) effect of biochar application on the total N fixed was observed in the second trial and the combined. Application of biochar significantly ($P<0.05$) increased the total N fixed of the crop from 124.5 and 90.9 kg ha^{-1} recorded in the treatments where no biochar was applied in the second trial and the combined, respectively to 163.4 and 114.1 kg ha^{-1}, respectively. However, in the first trial, the total N fixed (57.2-64.8 kg ha^{-1}) was not significantly ($P>0.05$) influenced by the application of biochar on the crop.

Effect of landrace

The total N fixed by the landraces in the first trial (60.7-61.3 kg ha^{-1}), second trial (142.5-145.5 kg ha^{-1}) and the combined (101.6-103.4 kg ha^{-1}) was not significantly ($P>0.05$) different between the landraces.

Effect of rock phosphate

The total N fixed in the rock phosphate treatments ranged from 55.0-64.4, 137.0-148.4 and 99.9-105.2 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly ($P>0.05$) influenced by the application of rock phosphate on the crop.

Interaction

No significant (P>0.05) interaction between the treatments on the total N fixed by the crop was observed during the trials.

Table 4. 3. 28: Total N fixed of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Total N fixed (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	57.2	124.5b	90.9b
10	64.8	163.4a	114.1a
SEM	3.55	11.15	5.85
P value	0.140	0.020	0.007
Landrace (L)			
Ex-Sokoto	60.7	142.5	101.6
Kaaro	61.3	145.5	103.4
SEM	3.55	11.15	5.85
P value	0.897	0.852	0.828
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	55.0	144.7	99.9
20	64.4	137.0	100.7
40	62.0	148.4	105.2
60	62.5	145.8	104.2
SEM	5.01	15.76	8.27
P value	0.574	0.961	0.961
Interaction P values			
B X L	0.108	0.982	0.633
B X RP	0.294	0.720	0.833
L X RP	0.548	0.673	0.904
B X L X RP	0.953	0.621	0.571

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.29 Soil N uptake

Soil N uptake of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.29.

Effect of biochar

Significant (P<0.05) effect of biochar application on soil N uptake of the crop was observed in the first trial and the combined. Application of biochar significantly (P<0.05) increased the soil N uptake of the crop from 48.5 and 55.1 kg ha^{-1} recorded in the first trial and the combined, respectively to 59.8 and 66.1 kg ha^{-1}, respectively. However, in the second trial, the soil N uptake of the crop (61.7-72.4 kg ha^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

Significant (P<0.05) difference between the landraces in the soil N uptake was observed in the combined and was higher (65.4 kg ha^{-1}) in Ex-Sokoto landrace than Kaaro landrace (55.8 kg ha^{-1}). However, the soil N uptake of the crop in the first (50.5-57.8 kg ha^{-1}) and second trial (61.2-73.0 kg ha^{-1}) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

The soil N uptake of the crop recorded in the rock phosphate treatments ranged from 49.8-58.4, 63.8-68.9 and 57.1-63.4 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant (P>0.05) interaction between the treatments on the soil N uptake of the crop was observed during the trials.

Table 4. 3. 29: Soil N uptake of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	Soil N uptake (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	48.5b	61.7	55.1b
10	59.8a	72.4	66.1a
SEM	3.55	4.13	2.72
P value	0.031	0.077	0.006
Landrace (L)			
Ex-Sokoto	57.8	73.0	65.4a
Kaaro	50.5	61.2	55.8b
SEM	3.55	4.13	2.72
P value	0.153	0.052	0.016
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	58.4	66.8	62.6
20	49.8	68.9	59.4
40	50.4	63.8	57.1
60	58.1	68.7	63.4
SEM	5.02	5.84	3.85
P value	0.461	0.920	0.633
Interaction P values			
B X L	0.429	0.440	0.269
B X RP	0.687	0.360	0.223
L X RP	0.467	0.851	0.742
B X L X RP	0.981	0.918	0.963

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.30 Nitrogen balance (+stover)

Nitrogen balance (+stover) of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.30.

Effect of biochar

Significant (P<0.05) effect of biochar application on the N balance (+stover) of the crop was observed in the second trial and the combined. Application of biochar significantly (P<0.05) increased the N balance (+stover) of the crop from 71.7 and 59.8 kg ha^{-1} recorded where no biochar was applied in the second trial and the combined, respectively to 102.7 and 77.6 kg ha^{-1}, respectively. However, in the first trial, the N balance (+stover) of the crop (47.8-52.5 kg ha^{-1}) was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

The N balance (+stover) recorded by the landraces in the first trial (46.6-53.8 kg ha^{-1}), second trial (80.0-94.5 kg ha^{-1}) and the combined (63.3-74.1 kg ha^{-1}) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

The N balance (+stover) of the crop recorded in the rock phosphate treatments ranged from 43.7-54.5, 80.9-96.0 and 62.3-74.4 kg ha^{-1} for the first trial, second trial and the combined, respectively and was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the N balance (+haulm) of the crop was observed during the trials.

Table 4. 3. 30: Nitrogen balance (+stover) of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	N balance (+stover) (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	47.8	71.7b	59.8b
10	52.5	102.7a	77.6a
SEM	3.26	9.41	4.98
P value	0.315	0.027	0.014
Landrace (L)			
Ex-Sokoto	46.6	80.0	63.3
Kaaro	53.8	94.5	74.1
SEM	3.26	9.41	4.98
P value	0.130	0.284	0.129
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	43.7	80.9	62.3
20	54.5	82.5	68.5
40	52.7	96.0	74.4
60	49.8	89.5	69.7
SEM	4.61	13.31	7.04
P value	0.381	0.844	0.685
Interaction P values			
B X L	0.162	0.855	0.769
B X RP	0.548	0.847	0.985
L X RP	0.324	0.637	0.938
B X L X RP	0.677	0.585	0.538

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.31 Nitrogen balance (-stover)

Nitrogen balance (-stover) of Bambara groundnut as influenced by biochar and rock phosphate levels and their interaction (P values) on tropical acidic soils is presented in Table 4.3.31.

Effect of biochar

No significant (P>0.05) effect of biochar application on the N balance (-stover) of the crop was observed in the trials. The removal of crop residues along with the grain (N balance (-stover)) resulted in soil N depletion of 32.1-41.3, 25.7-26.1 and 29.1-33.5 kg ha^{-1} in the first trial, second trial and the combined, respectively which was not significantly (P>0.05) influenced by the application of biochar on the crop.

Effect of landrace

Significant (P>0.05) difference between the landraces in N balance (-stover) was observed in the combined. Removal of the grains along with the residues showed that Ex-Sokoto landrace significantly (P<0.05) depleted higher (36.4 kg ha^{-1}) soil N than Kaaro landrace (26.3 kg ha^{-1}) in the combined. However, the soil N depletion in the first (33.0-40.5 kg ha^{-1}) and second trial (19.6-32.3 kg ha^{-1}) was not significantly (P>0.05) different between the landraces.

Effect of rock phosphate

The soil N balance (-stover) of the crop in the rock phosphate treatments showed soil N depletion of 31.4-42.7, 21.4-29.8 and 27.0-34.1 kg ha^{-1} in the first trial, second trial and the combined, respectively which was not significantly (P>0.05) influenced by the application of rock phosphate on the crop.

Interaction

No significant ($P>0.05$) interaction between the treatments on the N balance (-haulm) of the crop was observed during the trials.

Table 4. 3. 31: Nitrogen balance (-stover) of Bambara groundnut landraces as influenced by biochar and rock phosphate application at the Field Research Centre of the Crops For the Future

Treatments	N balance (-stover) (kg ha^{-1})		
	First trial	Second trial	Combined
Biochar (B) (t ha^{-1})			
0	-32.1	-26.1	-29.1
10	-41.3	-25.7	-33.5
SEM	3.42	4.87	2.97
P value	0.067	0.954	0.300
Landrace (L)			
Ex-Sokoto	-40.5	-32.3	-36.4b
Kaaro	-33.0	-19.6	-26.3a
SEM	3.42	4.87	2.97
P value	0.129	0.076	0.019
Rock phosphate (RP) (kg P_2O_5 ha^{-1})			
0	-42.7	-25.4	-34.1
20	-31.4	-29.8	-30.6
40	-32.6	-21.4	-27.0
60	-40.2	-27.1	-33.6
SEM	4.83	6.88	4.21
P value	0.285	0.856	0.619
Interaction P values			
B X L	0.736	0.502	0.455
B X RP	0.764	0.485	0.439
L X RP	0.550	0.861	0.674
B X L X RP	0.980	0.585	0.742

Means followed by same letter(s) within a column are not significantly different at 5% level using Duncan's Multiple Range Test. P values = Probability values, SEM = Standard error of mean

4.3.32 Correlation studies

4.3.32.1 Correlation coefficients among the agronomic traits

The correlation coefficients between agronomic traits (combined trials) is presented in Table 4.3.32.1

The correlation studies revealed the grain yield of the crop to be positively correlated with the number of leaves per plant (0.449**), leaf area (0.302**), leaf area index (0.301**), NDVI (0.632**), pod weight (0.998**), number of pods plant^{-1}, shelling percentage (0.577**), plant dry weight (0.814**), 1000-grain weight (0.891**) and harvest index (0.433**). However, it was negatively correlated with days to 50 % flowering (-0.653**). The grain yield of the crop was not significantly ($P>0.05$) correlated with plant height (0.131^{ns}) and haulm weight (0.115^{ns}).

4.3.32.2 Correlation coefficients among physiological traits, agronomic traits (grain and plant dry weight) and N fixation related traits

The correlation coefficients between physiological traits, agronomic traits (grain and plant dry Weight) and N fixation related traits (combined trials) is presented in Table 4.3.32.2

The total N fixed by the crop was positively correlated with leaf photosynthesis (0.730**), grain yield (0.811**), plant dry weight (0.914), total N content (0.931**), N harvest index of the grain (0.545**) and % N derived from the atmosphere (0.796**), soil N uptake (0.313**), N balance (+stover) (0.923**) and N balance (-stover) (0.487**).

Table 4. 3. 32. 1: Pearson correlation coefficients among agronomic traits (Combined trials)

	PlH	LN	LA	LAI	NDVI	D50%Flwr	Pod-Wgt	Pod-Plt^{-1}	Grain-kg	Shell%	Haulm-kg	Dry-wgt	1000GWt	HI
PlH	1													
LN	.597**	1												
LA	.650**	.891**	1											
LAI	.650**	.891**	1.000**	1										
NDVI	.624**	.777**	.720**	.719**	1									
D50%Flwr	-.264**	-.366**	-.330**	-.330**	-.613**	1								
Pod-wgt	.145	.465**	.320**	.319**	.650**	-.659**	1							
Pod-Plt^{-1}	.130	.443**	.270**	.269**	.613**	-.628**	.959**	1						
Grain-kg	.131	.449**	.302**	.301**	.632**	-.653**	.998**	.963**	1					
Shell%	-.254*	-.021	-.159	-.159	.108	-.312**	.539**	.547**	.577**	1				
Haulm-kg	.525**	.379**	.339**	.339**	.408**	-.090	.144	.153	.115	-.340**	1			
Dry-wgt	.404**	.562**	.430**	.430**	.717**	-.545**	.831**	.805**	.814**	.214*	.669**	1		
1000-Gwt	-.124	.216*	.088	.087	.396**	-.595**	.880**	.833**	.891**	.712**	-.248*	.521**	1	
HI	.518**	.499**	.417**	.417**	.588**	-.305**	.462**	.451**	.433**	-.146	.943**	.876**	.070	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

PlH= plant height, LN= Number of leaves, LA=leaf area, LAI= leaf area index, NDVI=normalized difference vegetation index, D50%Flwr=days to 50% flowering, Pod-wgt=pod weight, Pod-plt^{-1}=Number of pods per plant, Grain-kg=grain weight, Shell%=shelling percentage, haulm-kg=haulm weight, Dry-wgt=plant dry weight, 1000-Gwt=1000-grain weight, HI=harvest index.

Table 4. 3. 32. 2: Pearson correlation coefficients among physiological traits, agronomic traits (grain and plant dry weight) and N fixation related traits (Combined trials)

	SPAD	Photosyn	Grain	Dry-Wgt	TotNcont	NHIGrain	Ndfa	TotlNFix	SoilNupt	Nbal+stvr	N bal-stvr
SPAD	1										
Photosyn	-.287**	1									
Grain	-.346**	.856**	1								
Dry-Wgt	-.279**	.639**	.814**	1							
TotNcont	-.279**	.708**	.852**	.980**	1						
NHIGrain	-.295**	.881**	.879**	.528**	.583**	1					
Ndfa	-.215*	.559**	.513**	.546**	.548**	.337**	1				
TotlNFix	-.281**	.730**	.811**	.914**	.931**	.545**	.796**	1			
SoilNupt	-.134	.304**	.507**	.623**	.639**	.369**	-.252*	.313**	1		
Nbal+stvr	-.190	.494**	.527**	.790**	.789**	.210*	.831**	.923**	.106	1	
Nbal-stvr	-.095	.285**	.161	.135	.134	.083	.849**	.487**	-.677**	.618**	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
SPAD=chlorophyll content, Photosyn=photosynthesis, Grain=grain weight, Dry-Wgt=plant dry weight, TotalNcont=total N content, NHIGrain=nitrogen harvest index, Ndfa=nitrogen derived from the atmosphere, TotalNFix=total N fixed, SoilNupt=soil N uptake, Nbal+stvr=N balance (+stover), N bal-stvr=Nbalance (-stover).

CHAPTER FIVE

5. DISCUSSION

The discussion presented here summarizes the effect of various treatments on the performance of the crop across the experiments. The discussion on the effect of landrace considers all the three experiments (1, 2 and 3). However, the discussion on the effect of rock phosphate application considers experiment 2 and 3 because it was not included as a treatment in experiment 1. Likewise, the discussion on the effect of biochar is solely for experiment 3. The discussion on the main effect of the treatments in experiment 3 is based on the combined analysis (mean performance of the two trials) just like for the interaction effect of various treatments in the same experiment.

5.1 Effect of landrace

Bambara groundnut could be one of the potential crops of the future as this study confirms the wide-range adaptability of the crop from Arid and Semi-Arid sub-Saharan Africa where it originated to humid tropical region with acid soil conditions in Malaysia. Azam-Ali *et al*. (2001) and Mohale *et al*. (2014) had earlier suggested a wider adaptation of the crop. The varied performance of the landraces recorded in the present studies could be attributed to the differences in their genetic make-up and to the adaptation of the landraces to the present environment of study.

5.1.1 Experiment 1

Bambara groundnut showed luxuriant vegetative growth with plant height ranging from 18.3-19.7 cm and number of leaves per plant ranging from 44-49. These height and number of leaves per plant were within the ranges of 16.5-20.5 cm and 23-59 leaves, respectively recorded by Chijioke *et al*. (2010) in Nsukka, Southern Nigeria. Chlorophyll content which is an indication of plant health and N concentration (Okamoto and Okada, 2004) was generally in the range of 31.6 to 40.3. LAI ranged from 1.5-1.6 indicating that the landraces exhibited good growth occupying 1.5 times the land area they occupied within the 12 weeks after sowing. These results were however lower than 2.6-5.4 reported by Collinson *et al*. (1996) under irrigation experiment. The lower values recorded here could be due to differences in the landraces used and the environment under which the studies were carried out. Zahran *et al*. (1999) reported inadequate photosynthesis and soil acidity as typical environmental stresses faced by legumes in the wetter tropics. Soil acidity restricts legume growth due to its impact on N fixation (Appunu and Dhar, 2006).

The varied performance of the landraces in number of pods per plant (9-41), grain weight (703- 2256 kg ha^{-1}) and harvest index (43.4-26.1 %) could be attributed to the differences in their genetic makeup and adaptation of the landraces to various growing conditions. The grain yield (703- 2256 kg ha^{-1}) recorded during the study is within the ranges of 100-2470 kg ha^{-1} reported by Collinson *et al.* (1996) in a glasshouse study. The higher grain yield, pod yield and shell weight recorded by Ex-Sokoto landrace could be attributed to its superior performance in number of pods per plant, total dry weight and harvest index. The finding here supports that of Kishinevsky *et al*. (1996) who reported significant positive correlations among number of pods per plant, harvest index and grain yield. In a related study on chickpea (*Cicer arietinum* L.), López-Bellido *et al*. (2004) identified biomass and harvest index as the two parameters most closely related to the seed yield. The lower grain yield recorded by Kaaro and NN-1 landraces could be attributed to their lower performance in total dry weight and harvest index. Heller *et al*. (1997) reported that lower and sometimes zero yields were recorded in cream and white seeded landraces in Botswana.

The harvest index (26.1-43.4 %) recorded by the landraces during the trial was lower than the range of 44.7-62.5 % reported by Mkandawire and Sibuga (2002). The higher harvest index recorded by Ex-Sokoto landrace compared to the other landraces could be due to its higher grain yield which is in agreement with the findings of López-Bellido *et al*. (2004) on chickpea. Likewise, the shelling percentage (65.8-71.5 %) recorded which was not different among the landraces was within the range of 59-76 % reported by Kishinevsky *et al*. (1996).

The % N content derived from the atmosphere (43.4-73.7 %) and the N fixed (32-81 kg ha^{-1}) by the landraces were within the ranges of 33-98 % and 4-200 kg N ha^{-1}, respectively reported by Mohale *et al*. (2014) under farmers' condition in South Africa. The superiority of Ex-Sokoto landrace in N fixation compared to the other landraces could be due to its higher total dry weight since the percentage nitrogen derived from the atmosphere (43.4-73.7 %) and N concentration of the grains (3.4-3.7 %), haulm (2.3-2.4 %) and shells (1.3-2.1 %) were not significantly different among the landraces. Plant dry weight has been reported to be the driving factor behind N fixation (Unkovich and Pate, 2000; Carlsson and Huss-Danell, 2003; Herridge *et al*., 2008; Yang *et al*., 2010). Likewise, N fixation depends on photosynthesis to provide ATP for energy and carbon compounds as electron donors (Paul and Clark, 1996; Belnap, 2001) and hence, the higher performance of the landrace. The lower fixed N recorded by Kaaro and NN-1 landraces could be due to their lower performance in total dry weight.

The net nitrogen returns where only the grain was removed from the soil [N balance (+ haulm)] which was positive (1.0-25.6 kg N ha^{-1}) and not significantly different among the landraces could be due to the higher % Ndfa (43.4-73.7 %) than N-harvest index (35.5-56.6 %) recorded by all the landraces. Osunde *et al*. (2003) reported that positive N balance could be expected where % Ndfa exceeds N harvest index provided that the residue is not removed. However, the lower negative N returns recorded by NN-1 landrace where the haulm was removed along with the grain [N balance (-haulm)] compared to Ex-Sokoto landrace could be attributed to its lower grain yield and N-harvest index. This agrees with the finding of Osunde *et al*. (2003) and Adjei-Nsiah *et al.* (2008) who associated lower grain yield and N-harvest index with greater potential to contribute to soil N.

5.1.2 Experiment 2

The leaf area index recorded by the landraces which ranged from 0.45-0.80 and 1.24-1.81 at 4 and 8 weeks after sowing respectively, were lower than 2.6-5.4 reported by Collinson *et al*. (1996) under irrigation experiment. The difference of which could be attributed to the differences in the landraces used and the growing condition under which the two experiments were carried out. The height (22.5-23.8 cm) of the crop recorded at 8 weeks after sowing was higher than the 16.5-20.5 cm recorded by Chijioke *et al*. (2010) in southern Nigeria which could be attributed to the differences in the landraces used and the environments under which the studies were carried out. The number of leaves per plant at 8 weeks after sowing (46-48 leaves) falls within the range of 25-59 leaves reported earlier by Chijioke *et al*. (2010).

The higher shoot and plant dry weight recorded by Kaaro landrace at 4 WAS could be attributed to its higher performance in root length, volume, weight and surface area. FAO (2004) reported the superiority of high root density in exploring large soil volume for P and other nutrients. Likewise, shoot vegetative growth is reported to be directly associated with root growth due to more exploration of soil for nutrients (Hill *et al*., 2006). The non-significant difference between the two landraces in root growth and plant dry weight observed at 8 WAS shows that despite the differences in the early performance of the landraces the growth tends to be similar at later stage of growth. Therefore, the higher early growth observed in Kaaro landraces is attributed to its higher seed size (1000-grain weight) which could be due to its higher seed nutrients reserve and genetic make-up.

The higher grain and pod yield recorded by Kaaro landrace compared to Ex-Sokoto landrace could be attributed to its superior performance in plant dry weight than Ex-Sokoto. Since the shelling percentage, harvest index and number of pods plant^{-1} of the two landraces were not significantly (P>0.05) different. The harvest index (28.3-29.0 %) recorded by the landraces during the trial was lower than the range of 44.7-62.5 % reported by Mkandawire and Sibuga (2002). The difference of which could be attributed to the differences in the landraces used and the environment under which the studies were carried out. The shelling percentage (70.9-71.9 %) recorded by the landraces during the experiment falls within the range of 59-76 % reported by Kishinevsky *et al*. (1996).

The higher plant N content recorded by Kaaro landrace than Ex-Sokoto landrace confirms its superiority in both N fixation and the ability to explore larger soil volume for N and other nutrients which could be attributed to its higher performance in plant dry weight. Plant dry weight has been reported as a key driving factor in N fixation (Herridge *et al*., 2008). Graham and Vance (2000) reported that in legumes the amount of N fixed depends on shoot growth of the crop.

The % ndfa of the landraces (34.0-36.2 %) recorded in this experiment was higher than the 20 % reported by Kumaga *et al.* (1994) under greenhouse conditions at IAEA laboratory in Seibersdorf, Austria. Likewise, the N fixed by the landraces (587-894 mg plant^{-1}) was lower than the 1200 mg plant^{-1} recorded by Kishinevsky *et al*. (1996). The difference of which could be attributed to the differences in the landraces and to the environment under which the experiments were conducted. The higher performance of Kaaro landrace in % ndfa, N fixation and soil mineral N uptake could be attributed to its higher plant dry weight and N content than Ex-Sokoto landrace. Plant dry weight has been reported as the driving factor behind N fixation (Herridge *et al*., 2008; Yang *et al*., 2010).

The net nitrogen gains where only the grain was removed from the soil and the residues returned [N balance (+stover)] observed in this study which was positive and not significantly different between the landraces could be due to the higher % ndfa than N-harvest index recorded by both landraces. Osunde *et al*. (2003) reported that positive N balance could be expected where % ndfa exceeds the N harvest index of the crop provided that the residue is not removed. The depletion of the soil N as a result of the residues removal from the soil along with the grain [N balance (-stover)] observed in this study which was higher in Kaaro landrace could be attributed to its higher grain yield than Ex-Sokoto landrace since the N-harvest index of the two landraces was not significantly (P>0.05) different. The finding here agrees with the finding of Osunde *et al*. (2003) and Adjei-Nsiah *et al*. (2008) who associated lower grain yield and N-harvest index in legumes with greater potential to contribute to soil nitrogen.

5.1.3 Experiment 3

The plant height (19.8-20.5 cm) and number of leaves (56-57) per plant at 8 WAS which were not significantly different between the landraces were within the ranges of 16.5-20.5 cm and 23-59 leaves per plant, respectively reported by Chijioke *et al*. (2010). The leaf area index (1.547-1.870) of the landraces recorded at 8 weeks after sowing was lower than 2.6-5.4 reported by Collinson *et al*. (1996) under irrigation experiment which could be due to differences in the landraces used and the environment under which the studies were carried out. Zahran *et al*. (1999) reported inadequate photosynthesis and soil acidity as typical environmental stresses affecting legumes in the wetter tropics. The higher performance of Kaaro in leaf area index compared to Ex-Sokoto landrace could be attributed to its higher performance in the NDVI value which is another measure of plant vegetation.

The grain yield (891-1220 kg ha^{-1}) recorded in the trial was within the range of 100-2470 kg reported by Collinson *et al.* (1996) in a glasshouse study. The varied performance of the landraces in number of pods per plant (14-23 pods), pod yield (1330-1717 kg ha^{-1}) and grain yield (891-1220 kg ha^{-1}) could be attributed to the differences in their genetic make-up and to their adaptation to various growing conditions. The higher performance of Ex-Sokoto landrace in pod yield and grain yield compared to Kaaro landrace could be attributed to its higher performance in number of pods per plant and harvest index. Kishinevsky *et al*. (1996) reported significant positive correlations among number of pods per plant, harvest index and grain yield of the crop. Similarly, in a related study on chickpea (*Cicer arietinum* L.), López-Bellido *et al*. (2004) identified biomass and harvest index as the two most closely related parameters to the grain yield of the crop.

The shelling percentage (65.3-69.2 %) recorded by the landraces which was higher in Ex-Sokoto landrace was within the range of 59-76 % reported by Kishinevsky *et al*. (1996). The higher performance of Ex-Sokoto landrace compared to Kaaro could be attributed to its thinner shells. The harvest index (17.7-23.2 %) recorded by the landraces was lower than 44.7-62.5 % reported by Mkandawire and Sibuga (2002) the difference of which could be attributed to the differences in the landraces and the environment of the studies. The higher harvest index recorded by Ex-Sokoto landrace than Kaaro landrace could be due to its higher grain yield and shelling percentage compared to Kaaro landrace. This view is in agreement with the findings of López-Bellido *et al*. (2004) on chickpea. The higher 1000-grain weight recorded by Kaaro landrace compared to Ex-Sokoto landrace could be attributed to its genetic make-up.

The lack of significant difference between the landraces in the stover (2.77-2.83 %) and grain (3.25-3.36 %) N concentration could be explained by the similarity of the two landraces in chlorophyll content which has been reported as an indication of plant

N concentration (Okamoto and Okada, 2004). The higher grain N content recorded by Ex-Sokoto landrace could be attributed to its higher grain weight than Kaaro landrace because the grain N concentration of the landraces was not significantly different. The higher N harvest index recorded by Ex-Sokoto landrace could be attributed to its higher grain yield and harvest index than Kaaro.

The percentage N derived from the atmosphere of the landraces (50.1-53.8 %) which was not significantly different between the landraces was within the range of 33-98 % reported by Mohale *et al*. (2014). Similarly, the total N fixed (101.6-103.4 kg ha^{-1}) by the landraces which was not significantly different between the landraces was within the range of 4-200 kg ha^{-1} reported by Mohale *et al*. (2014).

The net N contribution of the landraces to the soil where only the grain was removed and the residues returned to the soil [N balance (+stover)] which was positive (63.3-74.1 kg ha^{-1}) and not significantly different between the landraces could be attributed to the higher % ndfa than N harvest index recorded by the landraces. Osunde *et al*. (2003) reported that positive N balance could be expected where % ndfa exceeds N the harvest index provided that the residues are not removed. The higher net soil N depletion recorded in Ex-Sokoto landrace (-36.4 kg ha^{-1}) due to removal of residues along with the grain [N balance (-stover)] compared to -26.3 kg ha^{-1} observed in Kaaro landrace could be attributed to its higher grain yield and N harvest. This agrees with the findings of Osunde *et al*. (2003) and that of Adjei-Nsiah *et al*. (2008) who associated lower grain yield and N-harvest index in legumes with greater potential to contribute to soil N.

The positive correlation observed between the grain yield and most of the yield components measured suggests the importance of the parameters in determining the grain yield of the crop. Kishinevsky *et al*. (1996) reported significant positive correlations among the number of pods per plant, harvest index and grain yield of the crop. Similarly, in a related study on chickpea (*Cicer arietinum* L.), López-Bellido *et al*. (2004) identified biomass and harvest index as the two most closely related parameters to the grain yield of the crop. On the total N fixed, which was observed to be positively correlated to important yield parameters including grain yield, plant dry weight and total N content suggests the direct relationship of these parameters to N fixation. Plant dry weight has been reported as the most important parameter closely related to N fixation in legumes (Herridge *et al*., 2008; Yang *et al*., 2010).

5.2 Effect of rock phosphate application

The response of the crop to rock phosphate as a source of P observed in experiment 2 could be attributed to the lower soil P status of the experimental site, the high P requirement of the crop and to the lower soil pH of the soil used (Table 3.2.1) which enhances the dissolution of the applied RP source in the study area. These attributes were earlier suggested as conditions for using rock phosphate in addressing the P constraint that limits crop production and in particular legume crops such as Bambara groundnut (FAO, 2004; Musa *et al*., 2012).

5.2.1 Experiment 2

The higher root weight, length, volume and surface area recorded in the treatments where rock phosphate was applied (20-60 kg P_2O_5 ha^{-1}) compared to the treatments where no rock phosphate was applied (0 kg P_2O_5 ha^{-1}) could be attributed to the role of phosphorus in root growth and development and hence, the more exploration of soil nutrients and this could explain the higher growth performance of the treatments which received application of rock phosphate. Jensen *et al*. (2002) reported low P concentration in plants to induce lower plant performance in root growth and shoot dry content. Likewise, Liao *et al*, (2001) reported phosphorus to promote root growth in common bean.

The higher root/shoot ratio observed in the treatments where no rock phosphate was applied (0 kg P_2O_5 ha^{-1}) compared to other treatments (20-60 kg P_2O_5 ha^{-1}) indicates that the plant invested higher proportion of its dry matter in root growth as compared to treatments that received rock phosphate application. This is because most plant species are reported to increase the proportion of dry matter allocated to the root system in response to P deficiency (Hill *et al*., 2006).

The higher shoot and plant dry weight recorded in the treatments that received rock phosphate application which was maximized at the application of 40 kg P_2O_5 ha^{-1} at 8 WAS harvest suggest that application 40 kg P_2O_5 ha^{-1} was optimum for the growth of the crop. Similarly, the higher haulm and total plant dry weight recorded at harvest in the treatments which received rock phosphate application of 20-60 kg P_2O_5 ha^{-1} which was not significantly different between the rates, compared to control (0 kg P_2O_5 ha^{-1}) could be because of the supply of P by rock phosphate which resulted in the increased availability and uptake of the nutrient by the crop. P is reported to play a major role in plant photosynthesis, energy metabolism and plant growth. The lower shoot and plant dry weight observed in the treatments where no rock phosphate was applied could be due to the low and limiting P supply which eventually reduces plant photosynthesis, energy metabolism and plant growth (Raghothama, 1999; Jensen *et al*., 2002).

The higher number of pods plant^{-1} observed in the rock phosphate applied treatments which was not significantly different between the rock phosphate levels (20-60 kg P_2O_5 ha^{-1}) could be attributed to the immense role of P in plant nutrition (Jensen *et al*., 2002) and hence, the more number of pods plant^{-1} recorded in the treatments where rock phosphate was applied. The increase in pod and grain yield of the crop due to rock phosphate application which were maximized at the application of (40-60 kg P_2O_5 ha^{-1}), and the haulm and total dry weight of the crop which were maximized at 20-60 kg P_2O_5 ha^{-1} could be attributed to the role of P in plant growth and development and hence the higher yield of the crop in the rock phosphate applied treatments (Graham and Vance, 2000). This suggests that application rock phosphate at 40 kg P_2O_5 ha^{-1} is optimum for the crop.

The higher N content, N fixed and soil mineral N uptake recorded in the treatments which received rock phosphate application of 20-60 kg P_2O_5 ha^{-1} compared to the treatments where no rock phosphate was applied (0 kg P_2O_5 ha^{-1}) which was not significantly different between the rock levels could be attributed to the supply of P by the applied rock phosphate which is of high requirement by legumes for N fixation. Graham and Vance (2000) reported that the higher P requirement by legumes is attributed to their higher ATP requirements for nitrogenase activity, nodule development and function.

The higher pod and grain yield of the crop recorded at the rock phosphate application 40 kg P_2O_5 ha^{-1} compared to other treatments shows that Christmas Island Rock Phosphate could serve as alternative source of P for the production of Bambara groundnut and thus, application rate of 40 kg P_2O_5 ha^{-1} (0.56 g kg^{-1} soil) was optimum for the crop.

5.2.2 Experiment 3

The lack of response to rock phosphate application in most of the parameters observed in this experiment compared to what was observed in experiment 2 could be due to the growing conditions in the field which are quite different from what is obtainable in the screenhouse. This is because the plants on the field interact with so many factors including rain, temperature and humidity. Again, the roots on the field are not limited by the size of the pot as the case in the screenhouse and can grow freely to explore larger volume of soil for moisture and nutrients.

The decrease in harvest index and N harvest index of the crop observed in the treatments where rock phosphate (20-60 kg P_2O_5 ha^{-1}) was applied compared to the treatments without rock phosphate application (0 kg P_2O_5 ha^{-1}) suggests a negative response of the two parameters to the applied rock phosphate. Graham and Vance (2000) reported P application in legumes to be essential due to higher ATP requirements for nitrogenase activity, nodule development and function. However, it does not come as a surprise because the response of crops to rock phosphate application like other forms of P fertilizer depends on the crop, the soil P status and pH (FAO, 2004).

5.3 Effect of biochar application

Biochar application on Bambara groundnut could be a sustainable way to increase the performance of the crop in the present environment of study and beyond. The remarkable increase in the performance of the crop observed as a result of biochar application confirms its immense role in improving the soil conditions for increased yield of crops. It also, shows that Bambara groundnut like other crops could benefit from the use of biochar and hence, an option for increasing the yield of the crop in the study area.

The increase in plant height, number of leaves, leaf area, leaf area index and NDVI in the treatments where biochar was applied could be due to increased nutrients availability and reduced N leaching. Lehmann *et al*. (2003) reported biochar addition to increase plant growth and nutrition and attributed it to the increase in nutrients availability and reduced leaching of N in the biochar applied treatments.

The increase in pod yield, grain, shell, haulm, stover and total dry weight of the crop recorded in the treatments where biochar was applied could be due to enhanced cation exchange capacity of the soil and resultant increase in nutrients availability.

Major *et al*., (2010) reported biochar application on highly weathered tropical soils to increase the soil nutrients availability and uptake in maize. Research conducted on Ferrosol to study the effect of biochar application on the agronomic performance of corn showed significant increase in the shoot dry weight of the crop and was attributed to the release of nutrients from the biochar and biochar's liming effect which resulted in increased nutrients availability (Smider and Singh, 2014).

The higher grain N content, Stover N content and total N content recorded with biochar application could be due to increased grain, haulm and total dry weight recorded as a result of biochar application. This is because the N concentration of both the grain and the stover was not influenced by the application of biochar on the crop. This agrees with the earlier report by Herridge *et al*. (2008) who reported yield and dry weight as key factors in determining plant N content.

The higher fixed N, soil N uptake and N balance (+haulm) of the crop recorded in the treatments where biochar was applied could be attributed to the increased plant dry weight recorded in the biochar applied plots since, the % ndfa of the crop was not significantly influenced by biochar application on the crop. Plant dry weight has been reported as the key driving factor behind N fixation (Herridge *et al*. 2008; Yang *et al*. 2010). Likewise, the higher grain harvest index and N harvest index recorded in the treatments where no biochar was applied could be because of the lower stover and total dry weight recorded in the biochar applied treatments.

The lower soil N depletion as a result of stover removal along with the grain [N balance (-haulm)] which occurred in the treatments where no biochar was applied compared to the treatments which received biochar application could be due to the lower total plant dry weight recorded in the experiment. This agrees with the earlier finding by Osunde *et al*. (2003) and Adjei-Nsiah *et al*. (2008) who associated lower grain yield and N-harvest index in legumes with greater potential to contribute to soil nitrogen.

5.4 Interactions

The higher pod yield, grain yield and shell weight recorded in the treatments which received only biochar application compared to other treatments that received combination of biochar and rock phosphate or rock phosphate alone suggests that application of biochar alone was sufficient to increase the yield performance of the crop. Biochar has been reported to raise soil pH and increase the availability of nutrients for crop uptake which could be the reason why addition of rock phosphate on those plots that already received biochar application did not result in any significant yield increase. Asai *et al*. (2009) observed reduction in soil nutrients uptake of upland rice in plots where biochar was applied despite the improved soil physical properties and P availability.

The positive response of grain N concentration in Ex-Sokoto landrace to biochar application as contrary to Kaaro indicates a variation in the two landraces in N demand and utilization with Ex-Sokoto landrace having higher N requirement than Kaaro. This could be attributed to the role of biochar in mobilization and retention of soil nutrients and making it more readily available for uptake by crops. Jin *et al*. (2016) reported that biochar could mitigate nitrate leaching by inhibiting the mineralization of organic N to ammonia and to nitrate or by adsorbing ammonium or nitrate, thus rendering it less available for leaching.

The higher grain N content and N harvest index observed in the treatments which received sole application of biochar compared to other treatments which received the combination of biochar and rock phosphate or rock phosphate without biochar suggests that rock phosphate application had a negative interaction with the biochar and the reason could be because biochar has the ability to mobilize soil nutrients including N and P for use by crops thereby reducing the high demand for external P by the crop, whereas rock phosphate upon dissolution adds P to the soil which in this case appears to have toxic effect on the crop. Zwieten *et al*. (2010) reported increased N retention due to biochar application and a reduced N fertilizer input demand while maintaining crop productivity. Biochar is also known to raise soil pH and thereby making the soil P more readily available for crop uptake which can make additional P from rock phosphate to have a negative effect on the crop. Yamato *et al*. (2006) found biochar application to decrease the exchangeable Al^{3+} content of the soil by increasing the pH of the soil. It also increased the available P contents, cation exchange capacity, exchangeable cations and base saturation of the soil. The total plant N content was also increased by the application of biochar (Yamato *et al*., 2006).

The decrease in the N harvest index of the crop in the treatments where biochar was combined with rock phosphate as compared to the sole biochar plots could be as a result of lower grain yield recorded in the treatments where biochar was combined with rock phosphate application.

CHAPTER SIX

6. SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 Summary

6.1.1 Effect of landrace

In experiment 1, the results revealed that Ex-Sokoto landrace was higher than the other landraces (Kaaro and NN-1 landraces) in number of pods per plant, pod weight, shell weight, grain weight, haulm weight, total dry weight, harvest index, grain N content, N harvest index total N content and N fixed. However, it was lower in N balance (-haulm) than the other landraces. Other parameters measured were not significantly different between the landraces.

In experiment 2, the results revealed higher performance of Kaaro landrace than Ex-Sokoto in pod weight, grain weight, haulm weight, total dry weight, 1000 grain weight, N content, N harvest index, % ndfa, N fixed and soil mineral N uptake. However, Ex-Sokoto landrace was higher in N balance (-stover). Other parameters measured were not significantly different between the landraces.

In experiment 3, it was observed that Kaaro landrace was higher in leaf area and leaf area index at all sampling dates and 1000-grain weight. Whereas, Ex-Sokoto landrace was higher in number of pods per plant, pod yield, grain yield, shelling percentage, harvest index, grain N content, N harvest index, soil N uptake and N balance (-stover). Other parameters measured were not significantly different between the landraces.

The grain yield and N fixed are comparable to the yields obtained in other regions and hence, Bambara groundnut is adapted to the acid soils of the study area. Ex-Sokoto landrace performs better in the region in terms of yield and N fixation than Kaaro landraces.

6.1.2 Effect of rock phosphate levels

In experiment 2, application of rock phosphate on the crop increased the plant height, number of leaves, LAI, shoot dry weight and plant dry weight at all sampling dates, final root length, volume, weight and surface area. It also increased the number of pods plant^{-1}, pod weight, grain weight, haulm weight, total dry weight, grain N concentration, total plant N content, N harvest index, N fixed and soil mineral N uptake with the grain and pod yield optimum at 40 kg P_2O_5 ha^{-1} (0.56 g kg^{-1} soil).

In experiment 3, application of Christmas Island Rock Phosphate (20-60 kg P_2O_5 ha^{-1}) decreased the harvest index of the crop compared to the treatments which received 0 kg P_2O_5 ha^{-1}. Similarly, the N harvest index of the crop was lower at the application of 40 kg P_2O_5 ha^{-1} than in other treatments. Other parameters measured were not significantly influenced by the application of rock phosphate on the crop.

6.1.3 Effect of Biochar

Application of biochar increased the plant height, leaf area and leaf area index of the crop at 6 and 8 WAS. It also increased the number of leaves per plant, NDVI at all sampling dates and transpiration at 4 WAS. Similarly, application of biochar increased the pod yield, grain yield, shell weight, haulm weight, stover weight and total dry weight of the crop. It also increased the grain N content, stover N content, total N content, N fixed in the shoot, total N fixed, soil N uptake and N balance (+haulm). It also led to more soil N depletion where the residues were removed along with the grain [N balance (-haulm)].

Application of biochar decreased the leaf photosynthesis of the crop at 8 WAS, shelling percentage, harvest index and N harvest index of the crop. other parameters were not influenced by the application of biochar on the crop.

6.2 Conclusions

The crop recorded grain yield and N fixed ranging from 703-2256 kg ha^{-1} and 32-81 kg ha^{-1}, respectively in experiment 1, 13.2-18.0 g $plant^{-1}$ and 587-894 mg $plant^{-1}$, respectively in experiment 2 and 891-1220 kg ha^{-1} and 101.6-103.4 kg ha^{-1}, respectively in experiment 3, which are comparable to the yields obtained in other regions. Hence, Bambara groundnut is adapted to the growing conditions in the study area. The two field experiments confirmed Ex-Sokoto landrace to perform better in terms of yield than Kaaro landrace in the study area. Growing Bambara groundnut and returning the residues back to the soil resulted in net addition of N to the soil in the range of 1 to 25.6 kg ha^{-1}, 150-261 mg $plant^{-1}$ and 63.3-74.1 kg ha^{-1} observed in experiment 1, 2 and 3, respectively. Application of biochar increased the yield and nitrogen fixation of the crop in the study area. However, the effect of rock phosphate application on the yield and N fixation of the crop was only observed in the screenhouse studies and was optimum at the application rate of 40 kg P_2O_5 ha^{-1} (0.56 g kg^{-1} soil).

Thus, Ex-Sokoto landrace could be recommended for grain yield in the study area. Application of biochar at 10 t ha^{-1} alone was optimum for increased yield of the crop. The implication of the study is that farmers in the study area could apply 10 t ha^{-1} of biochar on Ex-Sokoto landrace to enhance the yield of the crop.

6.3 Future work

The main objective of this study as a pioneer research on the crop in the study area was to investigate the growth, yield and nitrogen fixation of the crop and provide information that will lead to more researches on the crop in the region. The main objective was successful as it provides a comparable growth and yield of the crop to other regions. Similarly, the performance of the crop at biochar application was successful as it increases the performance of the crop in the two trials conducted and the combined. However, the effect of rock phosphate application on the crop was only observed in the screenhouse study.

While this study provides a significant contribution to the understanding of the crop's performance in the study area, further studies are needed to:

1- Evaluate the effect of other agronomic practices such as spacing, planting date and the response of the crop to other nutrients
2- P fractions of the soil as affected by biochar application
3- Compare other types of rock phosphates on different soil series and different locations for at least 3-5 cropping seasons
4- Carryout similar experiments on organic soils such as peat soil or Mollisols and Andisols
5- Conduct economic viability of including rock phosphate and biochar in Bambara groundnut cultivation in the tropics

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