OPTIMIZING P AND K FOR IMPROVING BIOLOGICAL NITROGEN FIXATION AND PRODUCTIVITY OF BAMBARA GROUNDNUT (*VIGNA SUBTERRANEA*) IN SOUTH-EASTERN TANZANIA

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOIL SCIENCE OF SOKOINE UNIVERSITY OF AGRICULTURE, MOROGORO, TANZANIA.

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EXTENDED ABSTRACT

Bambara groundnut (*Vigna subterranea* (L) Verde) is a pulse crop cultivated by smallholder farmers in Tanzania, ranked the third most important legume in the SEZ after pigeon pea (*Cajanus cajan*) and cowpea (*Vigna unguiculata*). Farmers in south-eastern Tanzania grow Bambara groundnut primarily for food and sell part of the produce to supplement income of their household. However, the productivity of Bambara groundnut is below the potential yield (< 2 t ha^{-1}), and is considered a threat to their livelihood. Among the factors causing low yields of Bambara groundnut include insect pests and disease incidences, poor agronomic practices and low soil fertility. Low soil fertility is amplified by continual mining of nutrient elements from the soil and reduction of soil organic matter content, through the removal and burning of crop residues and without applying balanced nutrients. Balanced supply of plant nutrients is important in order to improve and sustain yields of Bambara groundnut in South-Eastern Zone (SEZ). However, the establishment of the technologies of soil fertility management is hindered by inadequate information on soil characterization and classification of soils. These agronomic experiments would lead to establish technology that would be transferred to other areas of similar soil conditions for Bambara groundnut production, particularly in Tanzania. Furthermore, all developed interventions concentrated on improving Bambara groundnut varieties; plant spacing, morphology and diversity of the crop are known. The information on soil nutrient status including phosphorus (P) and potassium (K) for SEZ is not well known, and the required optimum rates are not yet established. Therefore, the intention of this study was to determine the status of soil fertility and optimum rates of N, P and K for Bambara groundnut production in the SEZ. A standard survey was carried out in the Bambara groundnut growing areas of SEZ, to establish representative experimental sites on the basis of agro-ecological settings and soils. The morphology, genesis, physio-chemical properties and classification of soils based on two international soil classification systems, namely USDA Keys to Soil Taxonomy and the World Reference Base (WRB), were assessed. Three pedons were characterized, namely NNL-P1 at Nannala village in Tandahimba district, MKG-P1 at Mikangaula village and NWJ-P1 at Nawaje village in Nanyumbu district. Disturbed and undisturbed soil samples from genetic soil horizons were analyzed for physico-chemical properties. Soil nutrient status for macro-nutrients (N, P, K, Ca, Mg and S) and micro-nutrients (Fe and Zn) were assessed from 22 soil samples from Bambara groundnut growing areas of south-eastern Tanzania. Field experiments were established on two pedons, namely NNL-P1 and NWJ-P1. The experiments were used to establish optimum rates of P and K for N_2 fixation and yields of Bambara groundnut in south-eastern Tanzania. The treatments for the field experiments were varied rates and combinations of P (0, 20, 40, or 60 kg P ha^{-1}), K (0, 40 or 80 kg K ha^{-1}) and N (0, 20 or 80 kg N ha^{-1}), as sub-plots, in a split plot design replicated three times. The main plots were two varieties of Bambara groundnut (local and improved). The characterization results indicated that two pedons NNL-P1 and MKG-P1 were classified to great group level using the USDA Keys to Soil Taxonomy as *Dystrustepts* and *Haplustepts*, respectively, and these translated into *Cambisols* in the WRB for Soil Resources. Pedon NWJ-P1 was classified as *Argiustolls* and translated into *Phaeozems* in the WRB. Over 60% of 22 soil samples analyzed for nutrient status, the limiting nutrients for productivity were N, P K, S, Mg and Zn, which were rated as being very low to low, while Ca was rated as medium in >80% of the soils of the studied areas. It was concluded that low nutrient status especially N, P, K, S, Mg and Zn, needs proper management to improve soil fertility for Bambara groundnut production. Application of P increased N_2 fixation and Bambara groundnut yield significantly. Thus, use of P at the rates of 20 – 40 kg P ha^{-1} is deemed necessary for high yields in the study area.

DECLARATION

I, John Jasper Tenga, declare to the senate of Sokoine University of Agriculture that this is my original work done within the period of registration and that is has neither been submitted nor being concurrently being submitted in any other institution.

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The above declaration is confirmed

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DEDICATION

This thesis is dedicated to almighty God, father of our Lord Jesus Christ: To Him be all honour and glory. I also dedicate it to my father Jasper J. Tenga, and to the memory of my beloved mother, the late Makaoneka Shehumu, who laid my foundation of my education, without putting aside my beloved family, my wife Angela H. Mbaga and my daughter Joan, who motivated me to achieve this goal.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

<	Less than
>	Greater than
^{0}C	Degree Celsius
1M	One Molar
AEZ	Agroecological zone
Al	Aluminium
ANOVA	Analysis of variance
ASS	Atomic absorption spectrophotometer
Aw	Equatorial savannah with dry winter
BD	Bulky density
BS	Base saturation
C/N	Carbon: Nitrogen ratio
C2	Coastal zone two
Ca/Mg	Calcium: magnesium ratio
Ca^{2+}	Calcium ions
CEC NH_4OAc	Cation exchange capacity extracted using ammonium acetate
CEC_{clay}	Cation exchange capacity of clay
CEC_{soil}	Cation exchange capacity of soil
CH1	Coastal hinterland and plateau
cm	Centimetre
cmol (+) kg^{-1}	Centimole (+) per kilogram
CPh4	Semi humid plains on intermediate metamorphic rock block 4
CPh8	Semi humid plains on acidic metamorphic rock block 8
CV	Coefficient of Variation

dS/cm	deciSiemen per centimetre
DTPA	Diethylenetriamine penta-acetic acid
E5	Eastern plateau and mountain block five
EC	Electrical conductivity
et al	And others
FAO	Food and Agriculture Organization of the United Nations
Fe	Iron
gm	Gramme
GPS	Global Position System
IUSS	International Union of Soil Science
K	Potassium
K/TEB	Potassium: total exchangeable base ratio
K^+	Potassium ion
KCl	Potassium chloride
kPa	Kilopascal
m	Metres
masl	Metres above sea level
MCC	Munsel soil colour chart
mg kg^{-1}	Milligrams per kilogram
Mg/K	Magnesium: potassium ratio
mg m^{-3}	Milligramme per metre cube
Mg^{2+}	Magnesium ions
MKG-P1	Mikangaula village soil profile one
mm	Millimetre
N	Nitrogen
Na^+	Sodium ion

NNL	Nannala village
NWJ	Nawaje village soil profile
OC	Organic carbon
OM	Organic matter
P	Available phosphorus
P1	Soil profile one
pH	Negative logarithm of hydrogen ion concentration
SMR	Soil moisture regime
SSS	Soil Survey Staff
STR	Soil temperature regime
TEB	Total exchangeable base
TN	Total Nitrogen
USDA	United States Department of Agriculture
WRB	World Reference Base

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background Information

Bambara groundnut (*Vigna subterranea*, L. Verde) is a crop widely distributed in the whole of sub-Saharan Africa (SSA) (Hillocks *et al.*, 2012). Tanzania is among the producers of Bambara groundnut in SSA. It is the third most important legume crop after pigeon pea (*Cajanus cajan*, L.) and cowpea (*Vigna unguiculata*, L.) (Mwangwela *et al*., 2012). The crop has the potential to contribute to the food security and economic development of poor people living in the marginal environment of poor soils with little rainfall (Mkandawire, 2007). According to Mwangwela *et al*. (2012); the dried seeds of this crop contain on average 63% carbohydrate, 19% protein and 6.5% oil. Massawe *et al.* (2005) and Ellah and Singh (2008) revealed that the protein of Bambara groundnut contains higher quantities of the essential amino acids, methionine and lysine, than those of the proteins found in other legumes.

In the south eastern zone (SEZ), which includes Lindi, Mtwara and part of Ruvuma regions, Bambara groundnut is grown by mainly women, primarily as a food and cash crop for their livelihoods. About 70% of the smallholders farmers in SEZ grow Bambara groundnuts and 60% of the produce is sold to generate income. A survey conducted by Mponda *et al*. (2010) reported that average grain yields of bambara groundnut from smallholder farmers in SEZ range between 153 – 283 kg ha^{-1}, which is lower than the potential yields of 2,200 kg ha^{-1} (Collinson *et al.*, 2000). Generally, several factors are known to limit Bambara groundnut yields, which include insect pests and disease incidences (Akpalu *et al*., 2013), poor agricultural practices (Berchie *et al*., 2010) and low soil fertility (Tadele, 2017).

Studies carried out on soils of in the SEZ by Ngatunga (2001) and Dondeyne *et al.* (2003) revealed very low levels of macronutrients contents including nitrogen (N), phosphorus (P) and potassium (K) which in turn reduce the potential of the area for higher crop yields. Balanced plant nutrients are important in improving soil productivity of Bambara groundnut growing areas particularly in the south-eastern Tanzania. Poor soil fertility is amplified by continuous removal and burning of crop residues, nutrient mining by plants and leaching to the extent that it reduces the plant nutrient pool in the soil (Ngatunga, 2001; Kisetu *et al.*, 2013). The trends of low fertility status necessitate the need of establishing N, P, and K rates for application in the Bambara groundnut growing areas.

Based on nutrients available in the soil, the plant will benefit from the nutrients applied when the nutrients in the soil are below the critical levels. However, according to Liu *et al.* (2006), available soil nutrient levels permit better match of fertilizer application to crop nutrient demand. The transfer of fertilizer use technology to other places depends on the knowledge of soil type of cultivated land. This could only be possible when the cultivated land is characterized.

Some of the areas in the south-eastern zone have been characterized for the purpose of growing cashew trees and such technology can be transferred to other areas of similar conditions for the purpose of growing cashew. However, in the Bambara growing areas of SEZ, soils were not characterised, hence this study would contribute to the characterization of the soils in relation to the response of fertilizer use on Bambara groundnut production.

1.2 Bambara Groundnut Cropping System and its Importance in Tanzania

Bambara groundnut is a grain legume grown by smallholders in marginal areas of Tanzania. Most of Bambara groundnut is grown in semi-arid parts of Tanzania including central, western and south-eastern regions and in the relatively wetter areas of Lake Victoria (Marandu and Ntundu, 1995). The crop fetches nutritional importance to livelihoods of the people and livestock as well as nutrient replenishment in soils. Azam-Ali *et al*. (2001) reported that Bambara groundnut seeds are important for food security. It is a versatile crop which contains 18.8% protein, 6.25% oil and 61% carbohydrate in dried seeds which can be consumed in an immature state after grilling or boiling (Jakusko and Belel, 2009). According to Hillocks *et al.* (2012), sufficient quality of nut size, taste and high protein content, fresh Bambara groundnut has unique selling preposition.

The smallholder farmers grow Bambara groundnuts both in intercropping as well as sole crop in a monocultural system. It was reported that in Dodoma region, central Tanzania, Bambara groundnut is grown in a pure stand or in rotation with cereals such as maize or sorghum (Mkwachu, 2009). Hillocks *et al*. (2012) indicated that Bambara groundnut is suitable for intercropping systems with other crops and this practice encourages the crops to occupy only a small area of land but profitably.

In the south-eastern Tanzania, the smallholder farmers grow Bambara groundnut in monocropping and/or intercropped with maize, cassava, cashewnuts and pigeon peas in the Makonde Plateau. However, farmers residing on the inland plain grow Bambara groundnut as a monocrop. Mponda *et al*. (2010) reported that 85% of the households in the Makonde plateau were growing Bambara groundnuts, while 55% was reported in inland plains. Also, the author reported that Bambara groundnut is grown as a cash crop and as a food security crop for the family.

1.3 Problem Statements

1.3.1 Pedological characterization of soils in Bambara groundnut production areas in Tanzania

Pedological characterization is a systematic identification, grouping and delineation of various soils in a locality, which provides valuable information and knowledge on soil properties and gives clear understanding of morphological characteristics, physico-chemical and mineralogical properties in the area. Soils of SEZ include those of Makonde plateau and inland plain developed from parent materials with varied physical and chemical properties, and potential for Bambara groundnut production.

Low soil nutrient status and crop productivity are among the major constraints of smallholder farmer (Reynolds *et al*., 2015). According to Tully *et al*. (2015) removal of large amounts of nutrients from their soil through continuous cultivation and burning of crop residues without replenishment, results into low soil fertility. Most of the studies carried out in the SEZ reported low levels of nutrients in the Makonde and Inland plains soils (Majule and Omollo, 2008; Ngatunga *et al*., 2001a). Ngatunga *et al*. (2001b) established agronomic practices of cashew production in relation to soil properties in the cashew growing area of south-eastern Tanzania. The established agronomic technology could fit to other area with similar conditions. Transferring of the agronomic technology to other places requires well characterized soil and defined environmental characteristics (Msanya *et al*., 2016).

Some research studies in the SEZ have established pedological characterization of soils in the cashew growing areas (Dondeyne *et al*. 2003; Ngatunga *et al*. 2001a; Bennet *et al*. 1979). Small scale of 1:250,000 used by Bennett *et al*. (1979) was mostly suited for planning at regional level and not fit for the farm level planning. Kebeney *et al*. (2015)

reported that site specific characterization is important in order to generate information for the potential of the soils and appropriate soil management practices.

So, transferring knowledge of optimum fertilizer rates of N, P and K in Bambara groundnut growing areas in the SEZ and Tanzania in general might need the understanding of the prevailing soil type of a specific site. Therefore, there is a need of characterizing soils used in agronomic studies in the Bambara growing areas of SEZ.

1.3.2 The status of N, P and K in some soils of the south eastern Tanzania

Most of the soils in the Southern zone are highly weathered, with very low levels of plant nutrients, leading to low crop yields (Bennett *et al*., 1979). Poor soil nutrient status in the SEZ is further amplified by poor soil management, including clean weeding, inadequate fertilizer application and the removal and burning of crop residues. These practices contribute to continuous mining of nutrient elements from the soil and reduction of soil organic matter content which further intensifies soil fertility degradation. Ngatunga (2001) and Dondeyne *et al.* (2003) reported that soils in the SEZ had very low levels of N (< 0.11%), low P (Bray–1) (< 15 mg kg^{-1}) and low K (< 0.44 cmol (+) kg^{-1}), which in turn reduce the potential of the area for high crop yields. The low nutrient status of the soils in the SEZ indicates the need of N, P and K containing fertilizer supplementation for optimum crop production.

1.3.3 Nitrogen fixation potential of Bambara groundnut

Nitrogen (N) is among the vital elements needed for plant growth and production. Nitrogen gas constitutes approximately 80% in the earth's atmosphere, but it existis in form which is unavailable to plants (Santi *et al*., 2013). Biological nitrogen fixation is the process whereby nitrogen gas (N_2) from the atmosphere is converted to ammonia (NH_3)

which can be used by the plant to synthesize amino acids for plant growth (Wagner, 2011; Brad and Weil, 2008; Dashora, 2011).

Leguminous plants have the ability to convert N_2 to ammonia through biological nitrogen fixation (Santi *et al*., 2013). There are exceptions, however, where careful use of fertilizer nitrogen has increased yields and actually stimulated nitrogen fixation. Hardarson *et al*. (1984) reported that a small starter dose of 20 kg N/ha stimulated not only legume growth but N_2 fixation as well. Low availability of N in the soil makes use of small starter dose to stimulate the plant, and more N be compensated with fixed nitrogen. Most of N_2 fixation occurs in symbiotic relation within the host legume plant.

Some researchers have reported the potentials of leguminous plants to fix N_2. Graham and Vance (2003) reported that Bambara groundnut has the potential to fix nitrogen (N) in the soil, which is used for crop growth in the subsequent growing season. The amounts of fixed N_2 by legumes differ from one legume to another depending on the type of species in the cropping system. Giller (2001) reported that the N_2 fixation potential of cowpeas, groundnut and soybeans were 59 – 201, 21 – 206 and 55 – 188 kg N ha^{-1} $year^{-1}$, respectively. According to Weisany *et al*. (2013), low phosphorus contents of the soil may restrict root development and symbiotic N_2 fixation, thus leading to nitrogen deficiency. A study conducted by Yakubu *et al.* (2010) revealed that application of 40 kg P ha^{-1} increased N_2 fixation in cowpea, groundnut and Bambara groundnut by 378, 169 and 138%, respectively, over the control. The low level of P in sandy loam soils of Maiduguri University research farm in the North-eastern Nigeria indicated the need for application of P for increasing the N_2 fixation (Yakubu *et al*., 2010).

1.3.4 Yield potentials of Bambara groundnut in the cropping systems

Tanzania has a potential for increased Bambara production levels due to the strengths and available opportunities for Bambara and hence improved food security, nutrition and income of the farmers (Mwangwela *et al*., 2012). Most of the studies conducted were based on plant population, breeding, sowing dates of Bambara groundnut production (Mponda *et al*. 2010; Mkwachu, 2009; Mkandawire and Sibuga, 2002). The average yield of Bambara groundnut was 585.1 kg ha^{-1} under good agronomic practices in central zone (Dodoma and Singida) (Mkandawire and Sibuga, 2002). Mponda *et al*. (2010) reported that Bambara groundnut yield in SEZ was on average 285 kg ha^{-1} in soils of low fertility status.

On improving Bambara groundnut production, several researchers in other countries have reported that responses differed on application of P and or K containing fertilizers. Jana *et al*. (1990) reported that application of 50 kg K ha^{-1} increased the number of pods per plant, seed number per plant and weight of seeds. Wamba *et al*. (2012) also indicated that application of 100 kg K ha^{-1} increased Bambara groundnut yield by 70%. In Nigeria, application of P by Toungos *et al.* (2009) improved Bambara groundnut yields by 111% over the control. Jakusko and Belel (2009) reported that an application of P gave the highest seed yield by 31.8% increase. In Botswana, Ramolemana *et al*. (2000) reported that application of P with adequate soil moisture increased yields of Bambara groundnut from 2.8 to 4.2 t ha^{-1} in a sandy loam soil. Hassan and Ismail (2016) reported that application at 82.5 kg P ha^{-1} produced 1.93 t ha^{-1} of groundnut in Universiti Kebangsaan in Malaysia. A study by Wamba *et al*. (2012) in soils of University of Douala research farm in Cameroon found that application of 100 kg ha^{-1} of both P and K increased Bambara groundnut yield to the range of 4.03 to 8.6 t ha^{-1}. Since P and K are known to be deficient in some soils of SEZ application of P and K containing fertilizers becomes necessary for improving crop yields. Hence establishing optimum rates of these nutrients for Bambara groundnut production is worthwhile.

1.4 Justification of the Study

Bambara groundnut is crop cultivated for food and generating cash and is planted by 85 % of farmers, in the SEZ (Mponda *et al*., 2010). However, the yield levels in the SEZ are about 0.33 t ha^{-1} which is very low compared to the potential yield of 3 tons per hectare. Being a food and cash crop, the low yield means contributing more to poverty and hunger at household level (Hillocks *et al*., 2012). Since the deficiencies of N, P and K in soil have been reported in the SEZ (Majule, 1999; Ngatunga and Deckers, 2003), there is need to supplement these nutrient elements by using inorganic fertilizers to optimize crop production. Available evidence indicates that application of limiting nutrient levels in the soil under Bambara groundnut production, increased yield substantially. Application of limiting nutrients such as P and presence of adequate moisture would increase yield up to 2.8 to 8 t ha^{-1} (Ramolemana *et al*., 2000) in Botswana and (Wamba *et al*., 2012) in Cameroon. Therefore, the intention of this study was to generate information on N, P and K status and establish their optimum rates. Also classification of soils in Bambara growing areas will provide information on soils to reveal similarities that call for adoption of established fertilizer recommendations for Bambara groundnut production in specific areas in the SEZ and other areas with similar soils and agro-ecological zones.

1.5 OBJECTIVES

1.5.1 Overall objective

The overall objective of the study was to improve Bambara groundnut productivity which will result in improved farmers’ livelihood in the south-eastern Tanzania.

1.5.2 Specific objectives

(i) To characterize and classify the selected Bambara groundnut growing soils in the SEZ

(ii) To determine the soil fertility status in Bambara groundnut producing areas in the SEZ.

(iii) To quantify N_2 fixation capacities of the popular bambara groundnut landraces

(iv) To determine the response of Bambara groundnut to P and K fertilizers and establish optimum rates for maximizing yields and N_2 fixation.

1.6 Outline of the Thesis

This thesis is organized in six chapters: Chapter 1 presents a general introduction which provides the background information of Bambara groundnut production, the limiting nutrient investigations and the objectives which addressed the problems investigated in the study. Chapter 2 provides information of site specific soil characterization in terms of their pedological, morphological, physico-chemical properties and classification of the studied soils. The surface and subsurface soils, and limiting nutrients for crop production are discussed. Chapter 3 reported the soil nutrient status of macro and micro-nutrients in the studied area. The most limiting macro-nutrients, P and K of Bambara groundnut producing areas in the SEZ are discussed. Chapter 4 presents the response of popular Bambara groundnut varieties to macro-nutrients application and their effects on N_2 fixation are discussed. Chapter 5 discussed the response of the limiting macro-nutrients P and K to yields and yield attributes. Chapter 6 gives the general conclusions and recommendations of results of the series of experiments in chapters 2 to 5.

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CHAPTER TWO

2.0 PEDOLOGICAL CHARACTERIZATION AND CLASSIFICATION OF SOME TYPICAL SOILS IN TWO CONTRASTING AGRO-ECOLOGICAL SETTINGS OF THE SOUTH EASTERN TANZANIA

ABSTRACT

This study was carried out in South-Eastern Tanzania to establish representative experimental sites on the basis of agro-ecological settings and soils. Three pedons namely NWJ-P1 in Nawaje village, MKG-P1 in Mikangaula village and NNL-P1 in Nannala village were characterized. Soil moisture and temperature regimes in the study areas were ustic and isohyperthermic. Fifteen soil samples from genetic soil horizons were analyzed for physico-chemical properties. Pedons NNL-P1 and MKG-P1 had loamy sand topsoils overlying sandy loam to sand clay loam subsoils. Pedon NWJ-P1 had sandy clay loam topsoil overlying clay subsoil with indications of eluviation-illuviation as dominant pedogenic process. Whereas pedons NWJ-P1 and MKG-P1 were medium acid to slightly acid (pH 5.91 - 6.35), pedon NNL-P1 was extremely to very strongly acid (pH 4.36 - 4.57). Topsoil OC contents of the soils were very low to medium (0.49 to 1.28%) while subsoil OC values were very low to low (0.16 - 0.66%). Total nitrogen in the pedons were very low (0.02 - 0.07%), while C/N ratios generally ranged from 7 to 18 indicating good to moderate quality of soil organic matter. All studied soils were low in available P (Bray-1) (< 7 mg kg^{-1}) except topsoil of pedon NNL-P1 which had medium values (P range 7- 20 mg kg^{-1}). CEC values ranged from very low (< 6.0 cmol (+) kg^{-1}) to low (6.0 - 12.0 cmol (+) kg^{-1}). Percent base saturation of pedon NNL-P1 was medium (21 - 60) while pedons NWJ-P1 and MKG-P1 had high values (> 60%). Nutrient ratios Ca/TEB, Mg/K and % (K/TEB) indicated some degree of nutrient imbalance in the soils likely to impair nutrient

availability to plants. According to USDA Soil Taxonomy the pedons were classified as *Typic Dystrustepts* (pedon NNL-P1), *Typic Argiustolls* (pedon NWJ-P1) and *Typic Haplustepts* (pedon MKG-P1) which, according to WRB for Soil Resources, translated into *Dystric Cambisols*, *Luvic Phaeozems*, and *Eutric Chromic Cambisols*, respectively. In view of the study results, the studied pedons differed markedly in terms of pedological and physico-chemical properties, emphasizing the need to characterize soils before embarking on strategies and practices on soil fertility management for enhanced and sustained agricultural production. Sustainable cropping on the studied soils could be achieved by introduction of technologies suitable for rejuvenating soil fertility such as manuring, crop rotation, proper management of crop residues, fallowing, leguminous cover crops in the farming systems and use of fertilizers, particularly non-acidifying types of fertilizers.

Keywords: Pedological characterization, soil chemical characteristics, soil classification, soil morphological characteristics, soil physical characteristics, South-Eastern, Tanzania.

2.1 INTRODUCTION

Soil is a vital natural resource which plays an important role in plant growth and development for the livelihood of mankind. Pedological characterization as a systematic way of gathering soil information provides a clear understanding of soils in terms of their morphological, physical, chemical, biological and mineralogical properties; hence their potential and limitations for crop production (Msanya *et al*., 2003; Msanya *et al*., 2016). With increasing human population and farming activities, nutrient depletion has become a common phenomenon in most soils, hindering agricultural production (Pulakeshi *et al*., 2014).

Low soil fertility is currently being reported as the major factor contributing to low crop productivity in Tanzania, including the South-eastern areas under the current study (Bennett *et al*., 1979: Ngatunga *et al*., 2001a). The soils under study display remarkable variations in properties. According to Rajagopal *et al*. (2013), soil variations are influenced by many factors including nature of soil parent materials, climate and weathering trends over varying periods of time. Rajagopal *et al*. (2013) emphasized that spatial and temporal variations of soils need to be well characterized and classified to allow transfer of generated agronomic technologies to other areas of similar soil series.

The combination of soil characterization and classification provides valuable information and understanding of the physical, chemical, mineralogical and biological properties of the soils that alleviate the adverse effects of soil diversity and aid precision agriculture (Sharu *et al*., 2013; Ukut *et al*., 2014). Soil characterization provides the basic information necessary to create functional soil classification schemes and to assess soil fertility in order to unravel some unique soil problems in an ecosystem. In many locations, including those of the current study area in Tanzania (Makonde plateau and Inland plains), the availability and acquisition of the information is a challenge due to the fact that limited information has been generated relating to nutrient levels and their variations in the soils.

In the South-eastern Tanzania, two agro-ecological zones under the study, namely Makonde Plateau and the Inland Plains, represent a very potential agricultural area. It is the largest producer of cashewnuts (the second largest crop contributing to the economy of the country), pigeon peas, sesame, cassava and Bambara groundnut in Tanzania.

The early soil survey works carried out by Bennett *et al*. (1979) in South-eastern Tanzania covered the Makonde plateau and the inland plains at a reconnaissance scale of 1:250,000.

The nature of scale used in the above work is rather coarse and gives limited information for agricultural planning and experimentation purposes at farm level in the study area. A similar scenario was reported by Kebeney *et al*. (2015) and Msanya *et al*. (2016), where in their study areas it was necessary to carry out site-specific soil characterization in order to establish prevailing heterogeneity of the soils, and to establish their potential and appropriate management practices.

For appropriate decision making on sustainable use and management of soils as well as for improving agricultural production, there is a need for characterization and classification of soils of the study areas in a manner that will facilitate communication and transfer of knowledge to all end users of soil information, including farmers, extension staff and decision makers.

The main objective of the current study was to characterize the soils of the study areas in terms of their pedological, morphological and physico-chemical properties; and classify them using the USDA Soil Taxonomy (SSS, 2014) and the World Reference Base for Soil Resources (IUSS, 2015) to provide the base for improving soil management for increased crop yields.

2.2 MATERIALS AND METHODS

2.2.1 Description of the study area

The study was conducted in two Agro-ecological Zones (AEZs) defined on the basis of climate, soil type and elevation. The selected AEZs cover three villages including Nannala (Tandahimba district), Mikangaula and Nawaje (Nanyumbu district) with representative soil profiles designated as NNL-P1, MKG-P1 and NWJ-P1, respectively. The selection of villages was based on dorminant areas growing Bambara groundnut. The area is located approximately between Longitudes 38^{o} 03’ and 40^{o} 30’ E and latitudes 10^{o} 05’ and 11^{o} 25’

S with altitude ranging from 200 - 600 m.a.s.l. Figure 2.1 is a location map of the area showing among other features, positions of the studied soil profiles. Table 2.1 gives detailed salient characteristics of the study areas.

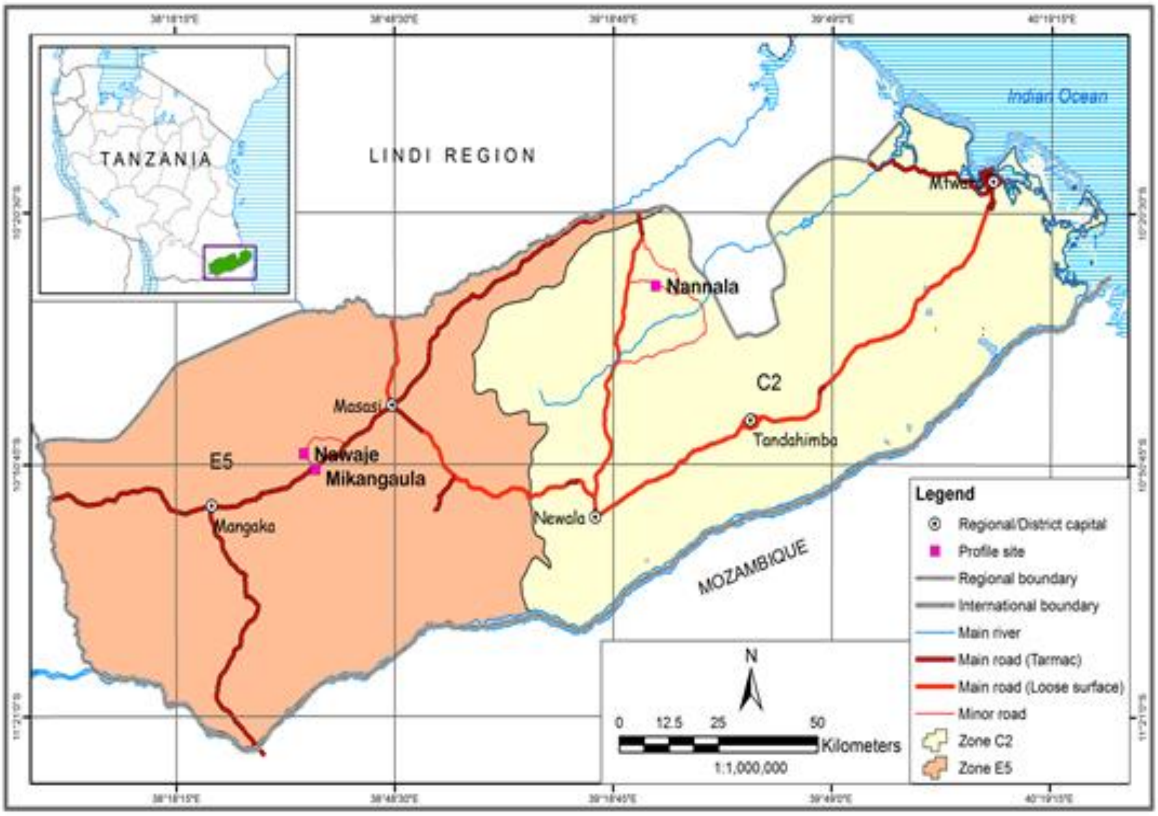

Figure 2.1: The location of soil pedon sites in the study area

2.2.2 Soils and physiography

The Nannala site is found in AEZ designated as Coastal zones (C2) in the Makonde plateau, and is characterized by nearly level to gently rolling plains and plateaux at an altitude below 500 m.a.s.l. The soils in this AEZ are well drained sands and sand loams developed on Neogene sandy clays, sandstone and other terrestrial sediments (De Pauw, 1984). Nawaje and Mikangaula sites are found in AEZ designated as Eastern plateaux and mountain block (E5) in the Inland Plains, characterised by level to rolling plains at an altitude of 200 - 500 m.a.s.l. with well drained soils developed on acidic and intermediate metamorphic rocks (De Pauw, 1984).

Table 2.1: Site characteristics of the studied pedons at Nannala, Nawaje and Mikangaula

Attributes	Description		
	Nannala (NNL-P1)	**Nawaje (NWJ-P1)**	**Mikangaula (MKG-P1)**
Coordinates	10° 29′ 15.7″ S, 039° 24′ 36.5″ E	10° 48′ 11.8″ S, 038° 36′ 32.8″ E	10° 52′ 39.1″ S, 038° 36′ 20.2″ E
AEZ#	CH1	CPh8	CPh4
Altitude (m.a.s.l)	525	359	335
Landform	Gently undulating to rolling plain	Level to rolling plain	Level to rolling plain
Geology/Lithology	Neogene sandstones	Intermediate metamorphic rocks	Acid metamorphic rocks
Slope %	2	1	2
Land use /Vegetation	Agriculture (groundnuts, cassava, pigeon peas, maize, Bambara groundnuts, cowpeas)	Agriculture (cowpeas, green gram, groundnuts, cassava, maize, Bambara groundnuts)	Agriculture (pigeon peas, groundnuts, maize, Bambara groundnuts, cassava)
Mean annual rainfall (mm)	800 - 1284 mm	600 - 1200 mm	600 - 1200 mm
SMR*	Ustic	Ustic	Ustic
Mean annual temperature ^{o}C	26^{o} C	24^{o} C	24^{o} C
STR	Isohyperthermic	Isohyperthermic	Isohyperthermic

#AEZ = Agro-Ecological Zone description:
CH1: Coastal zone (coastal hinterland plain and plateaux)
CPh8: Eastern plateaux and mountain block (semi humid plains on acidic metamorphic rock)
CPh4: Eastern plateaux and mountain block (semi humid plains on intermediate metamorphic rock)
*SMR = soil moisture regime, STR = soil temperature regime

2.2.3 Climate

The study area is influenced by the south-eastern trade winds in midyear and the north-eastern trade winds during the turn of the year. The study sites characteristically experience low, erratic and poorly distributed rainfall. The rainfall pattern is uni-modal. The rains start from December to April with a 2 - 3 weeks dry spell between the end of January and February of the year. The mean annual rainfall varies with altitude from 820 mm at around 100 m.a.s.l to 1245 mm at 870 m.a.s.l. The lowest mean monthly temperature is 24.3^{o} C occurring in July and the highest annual mean temperature is 27.5^{o} C in December. The mean annual temperature is 26^{o} C in the coastal area and 24^{o} C in the inland area (Ngatunga *et al*., 2001).

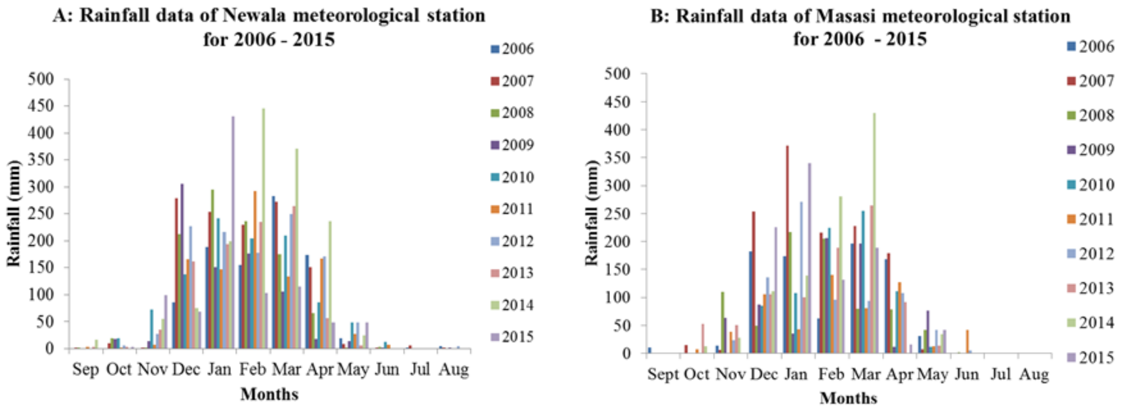

Figure 2.2: Mean monthly rainfall data collected at Newala Meteorological Station (AEZ C2) and Masasi Meteorological Station (AEZ E5)

2.2.4 Field methods

Transect walks, auger observations and descriptions to establish representative experimental sites were carried out. FAO guidelines for soil description (FAO, 2006) were used to describe landforms, elevation, slope gradient, parent material (lithology), vegetation and land use/crops of the selected sites. Soil morphological characteristics such as colour, texture, consistence, structure, porosity and effective soil depths were described according to FAO guidelines for soil description (FAO, 2006). Three representative soil profile pits of 2.5 m by 1.5 m for each selected site were excavated to a depth of 2 m and geo referenced using Global Positioning System model GARMIN (etrex 20). Disturbed soil samples were collected from each of the exposed genetic soil horizons whereas undisturbed soil samples (core samples) were collected at depths of 0 - 5, 45 - 50, and 95 - 100 cm, for laboratory analysis. Soil colour was determined by the use of soil colour chart (MCC, 1992).

2.2.5 Laboratory methods

Undisturbed core samples were used for determination of bulk density (BD) and soil moisture retention characteristics. Bulk density was determined by weighing soil cores after drying overnight at 105ºC (Blake, 1964). Soil moisture retention characteristics were studied using sand kaolin box for low suction values and pressure plate apparatus for higher suction values (Day, 1965; NSS, 1990). Available water capacity of soil was calculated as the difference in water retention between -33kPa and -1500 kPa (Lambooy, 1984). Disturbed soil samples from delineated horizons were used after air-drying, gently grinding and sieving through a 2 mm sieve for determination of physical and chemical properties.

Texture was determined by the Bouyoucos hydrometer method after dispersing soil with 5% sodium hexametaphosphate (Moberg, 2000). Textural classes were determined using USDA textural triangle (FAO, 2006). Soil pH was measured potentiometrically in water and in 1M KCl at the ratio of 1:2.5 soil: water and soil: KCl (Okalebo *et al*., 2002), respectively. Electrical conductivity (EC) was measured using an EC meter on 1:2.5 soil-water suspensions.

Organic carbon (OC) was determined by the Walkley and Black wet oxidation method (Nelson and Sommers, 1982), and the OC values converted to OM by multiplying with a factor of 1.724 (Duursma and Dawson, 1981). Total nitrogen was determined by micro-Kjedahl digestion-distillation method as described by Bremner and Mulvaney (1982). Available P was determined by the Bray and Kurtz-1 method (Bray and Kurtz, 1945). Cation exchange capacity of the soil (CECsoil) was determined from the same 1 M neutral NH_4OAc (ammonium acetate) extracts (Chapman, 1965). The CECclay was calculated by dividing CECsoil by percentage clay (x 100). The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+), were determined by atomic absorption spectrophotometer (AAS) (Anderson and Ingram, 1996). The total exchangeable bases (TEB) was calculated as the sum of the four bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+). Percent base saturation (PBS) values were obtained by dividing TEB by CECsoil and multiplying by 100.

2.2.6 Classification of the soils at the selected sites

Using field and laboratory analytical data, the soil pedons were classified to family level of the Soil Taxonomy (SSS, 2014) and to Tier-2 of the World Reference Base for Soil Resources (IUSS, 2015).

2.3 RESULTS AND DISCUSSION

2.3.1 Selected soil morphological characteristics

Some morphological characteristics of the studied pedons are shown in Table 2.2. All the pedons were very deep (> 150 cm) and somewhat excessively drained. The top soils of the three studied soils have loamy sand top soils overlying subsoils of varied textures. Whereas the subsoil of pedon NNL-P1 has sandy loam and clay texture, pedons NWJ-P1 and MKG-P1 have dominantly clay and sandy clay loam texture, respectively. Generally, pedons NNL-P1 and MKG-P1 have comparable texture, as they have formed from same parent materials under similar ecological conditions. The friable to very friable dark brown to brownish black topsoils of the three pedons indicates no restriction to root or water movement. The firm consistence in the subsoils of the three pedons may cause some restrictions to root growth particularly for deep rooted crops. The structure of the studied soils are subangular blocky throughout their depths, with grades ranging dominantly from weak (Pedon NNL-P1) to moderate (Pedon MKG-P1) and to strong (Pedon NWL-P1). The strong structure in the subsoil of pedon NWJ-P1 could be attributed to the high clay content in that soil. The observed structure of the studied soils suggest no restrictions to root growth, and unimpeded water movement. According to Brady and Weil (2008), the subangular blocky structure of the studied soils would promote drainage, aeration and root penetration. Common clay cutans were observed in the subsoil of Pedon NWJ-P1 suggesting that eluviation-illuviation is an important pedogenic process in this pedon.

Pedon NNL-P1 has gradual wavy soil boundaries whereas pedon NWJ-P1 has gradual smooth horizon boundaries.

Table 2.2: Morphological features of representative soil pedons of the study areas at Nannala, Nawaje and Mikangaula

Profile	Horizon	Depth (cm)	Texture[1)]	Moist colour[2)]	Consistence[3)]	Structure[4)]	Cutans[5)]	Horizon boundary [6)]
NNL-P1	Ap	0 - 25/30	LS	db (10 YR 3/3)	vfr, ns&np	w-f&m, sbk	-	gw
	AB	25/30 - 50/55	LS	dyb (10 YR 5/4)	fr, ns&np	w-f&m, sbk	-	gw
	Bw1	50/55 - 85/88	SL	dyb (10 YR 5/4)	fr, ns&np	w-f&m, sbk	-	gw
	Bw2	85/88 - 112/115	C	yb (10 YR 5/6)	fi, s&p	w-f&m, sbk	-	gw
	Bw3	115 - 160+	SL	yb (10 YR 5/6)	fr, ns&np	w-f&m, sbk	-	-
NWJ-P1	Ap	0 - 22/30	SCL	bb (5 YR 2/1)	fr, ss&sp	m-f&m, sbk	-	gs
	BA	22/30 - 52/60	SCL	drb (5 YR 3/4)	fi, ss&sp	m-f&m, sbk	-	gs
	Bt1	52/60 - 80/100	C	drb (5 YR 3/6)	fi, s&p	s-m&c, sbk	c,d,c	gs
	Bt2	80/100 – 140	C	rb (2.5 YR 4/6)	fi, s&p	s-m&c, sbk	c,d,c	gs
	Bt3	140 - 200+	C	rb (2.5 YR 4/6)	fi, s&p	s-m&c, sbk	c,d,c	-
MKG-P1	Ap	0 - 16/24	LS	drb (2.5 YR 3/2)	vfr, ns&np	w-f&m, sbk	-	cw
	AB	16/24 - 45/49	SL	drb (2.5 YR 3/4)	fr, ns&np	w-f&m, sbk	-	cw
	Bw1	45/49 – 103	SCL	rb (2.5 YR 4/6)	fi, ss&sp	m-m&c, sbk	-	gw
	Bw2	103 – 156	SCL	b (10 YR 4/6)	fi, ss&sp	m-f&m, sbk	-	gs
	Bwc	156 - 200+	SL	b (10 YR 4/6)	fr, ns&np	w-m&c, sbk	-	-

1) Texture: SL = sandy loam, LS = loamy sand, SCL=sandy clay loam, C=clayy
2) Colour: db = dark brown, dyb = dull yellowish brown, yb = yellowish brown, bb = brownish black, drb = dark reddish brown, rb = reddish brown, b = brown
3) Consistence: vfr = very friable, fr = friable, fi = firm, s = sticky, p= plastic, ss = slightly sticky, sp = slightly plastic, ns = non-sticky, np = non-
4) Structure: w-f&m = weak fine and medium, m-f&m = moderate fine and medium, s-m&c = strong medium and coarse, m-m&c = moderate medium and coarse, sbk = subangular blocky
5) Cutans: c=common; d=district; c=clay
6) Horizon boundary: g = gradual; c = clear; s =smooth; w = wavy

2.3.2 Soil physical characteristics

2.3.2.1 Soil particle distribution (texture), silt/clay ratio and bulky density (BD)

Table 2.3 presents physical properties of the studied soil pedons obtained from laboratory analysis. Texture is the most stable physical property which influences other soil properties like soil structure, consistence, soil moisture regime and infiltration rate, runoff rate, erodibility, workability, permeability, root penetrability and fertility of the soil (Landon, 1999).

Results in this study reveal that particle size distribution of the studied pedons are variable, but pedons NNP-P1 and MKG-P1 have similar textural classes, dominantly loamy sand and sandy loam. The similarities of the two pedons are attributed to the fact that the two profiles have developed under the same soil forming factors and have attained comparable degree of soil development. Shelukindo *et al*. (2014) reported similar results for some typical soils of Miombo wood lands. Pedon NWJ-P1, unlike other pedons, had sandy clay loam topsoil overlying a dominantly clay subsoil. The silt/clay ratios of 0.33 to 0.50, 0.10 to 0.40 and 0.36 to 0.65 were observed in pedons NNL-P1, NWJ-P1 and MKG-P1, respectively. The subsoil silt/clay ratios of pedon NWJ-P1 are lower than those of the other pedons indicating that pedon NWJ-P1 is more weathered than the other pedons. The decrease of silt/clay ratio values with depth indicates that subsoils are more weathered than topsoils. Karuma *et al*. (2015) reported similar results for soils of Busia County in Kenya.

Bulk density (BD) is an important parameter for the description of soil quality and ecosystem functions (Munishi, 2012). Topsoil bulk densities of the studied soils ranged from 1.35 to 1.48 mg m^{-3} while subsoil bulk densities ranged from 1.34 to 1.56 mg m^{-3} for all soil profiles (Table 2.3). Generally, BD increased with depth in the studied pedons.

The lower topsoil BD may be attributed to higher organic matter content (Dalal and Meyer, 1986). According to Brady and Weil (2008), bulk density increases with

Table 2.3: Selected physical properties of the studied pedons at Nannala, Nawaje and Mikangaula

Pedon	Horizon	Depth (cm)	Sand	Clay	Silt	Textural class	Silt/clay Ratio	BD (mg m^{-3})
				%				
NNL-P1	Ap	0 - 25/30	82	12	6	LS	0.50	1.48
	AB	25/30 - 50/55	82	12	6	LS	0.50	1.56
	Bw1	50/55 - 85/88	82	14	4	SL	0.29	nd
	Bw2	85/88 - 112/115	36	50	14	C	0.28	1.39
	Bw3	115 - 160+	76	18	6	SL	0.33	nd
NWJ-P1	Ap	0 - 22/30	72	20	8	SCL	0.40	1.38
	BA	22/30 - 52/60	48	46	6	SCL	0.13	1.51
	Bt1	52/60 - 80 /100	34	60	6	C	0.10	1.38
	Bt2	80/100 – 140	30	62	8	C	0.13	nd
	Bt3	140 - 200+	34	60	6	C	0.10	nd
MKG-P1	Ap	0 - 16/24	82	12	6	LS	0.50	1.35
	AB	16/24 - 45/49	74	18	8	SL	0.40	1.37
	Bw1	45/49 – 103	70	22	8	SCL	0.36	1.34
	Bw2	103 – 156	72	20	8	SCL	0.40	nd
	Bwc	156 - 200+	76	16	8	SL	0.50	nd

Texture: SL = sandy loam, LS = loamy sand, SCL=sandy clay loam, C=clay
nd = not determined

depth since the subsoils are more compacted, with less organic matter, aggregates and pore space, hence minimal numbers of roots compared to topsoils. The relatively higher subsoil BD values for pedons NNL-P1 and NWJ-P1 may pose a slight limitation to root penetration and water movement in these soils.

2.3.2.2 Soil moisture characteristics of the studied pedons

Table 2.4 presents results on soil moisture retention characteristics of the studied pedons. Soil water content in the three pedons decreased with increasing suction from saturation point to permanent wilting point. According to Haghnazari *et al*. (2015), soil particle size distribution, organic matter and soil type influence the variation of available moisture content in the soil. Plant available water for pedons NNL-P1, NWJ-P1 and MKG-1 ranged from 3.4 - 5.1%, 2.1 - 9.4%, and 4.6 - 6.2%, respectively. Plant available water increased with depth in pedon NNL-P1 and to some extent in pedon NWJ-P1, but there is no clear trend in pedon MKG-P1. However, higher water retention appears to be associated with higher clay contents (horizon BA of pedon NWJ-P1).

Table 2.4: Moisture content held at various suction pressures for the studied pedons at Nannala, Nawaje and Mikangaula

Profile	Horizon	Depth (cm)	0 kPa (SAT.)	10 kPa (FC)	25 kPa	100 kPa	1500 kPa (P.W.P.)	P.A.W. = (FC - P.W.P.)
NNL-P1	Ap	0 – 5	39.7	9.9	8.5	7	6.5	3.4
	AB	45 – 50	36	10.3	9.4	6.6	6.4	3.9
	Bw2	95 – 100	40.9	11.3	9.6	7.5	6.2	5.1
NWJ-P1	Ap	0 – 5	41.4	18.6	18.2	17.1	16.5	2.1
	BA	45 – 50	37.4	32.4	28.1	23.6	23	9.4
	Bt1	95 – 100	40.9	36.4	34.1	31.6	30.7	5.7
MKG- P1	Ap	0 – 5	46.7	12.8	9.7	7.1	6.6	6.2
	AB	45 – 50	37	13.7	11	9.5	9.1	4.6
	Bw1	95 - 100	31.5	15.8	12.5	11	10.6	5.2

Figure 2.3 presents the moisture retention curves of the studied pedons. The moisture retention curves of pedons indicate that at all soil matric suctions, the soil holds much more moisture at NWJ-P1 than the other two pedons. The higher moisture retention capacity of pedon NWJ-P1 is attributed to the higher clay content of the soil as compared to the other two pedons. According to Uwitonze *et al.* (2016), high ability of retaining water related to high clay content enables soils to hold more water, thereby contributing to moisture reserve for plants during the dry period. Although pedons NNL-P1 and MKG-P1 have comparable moisture retention behavior because of their similarity in texture, pedon NNL-P1 has the least moisture retention capacity of all the studied pedons.

2. 3.3 Soil chemical characteristics

Some selected soil chemical characteristics of the studied pedons are presented in Table 2.5.

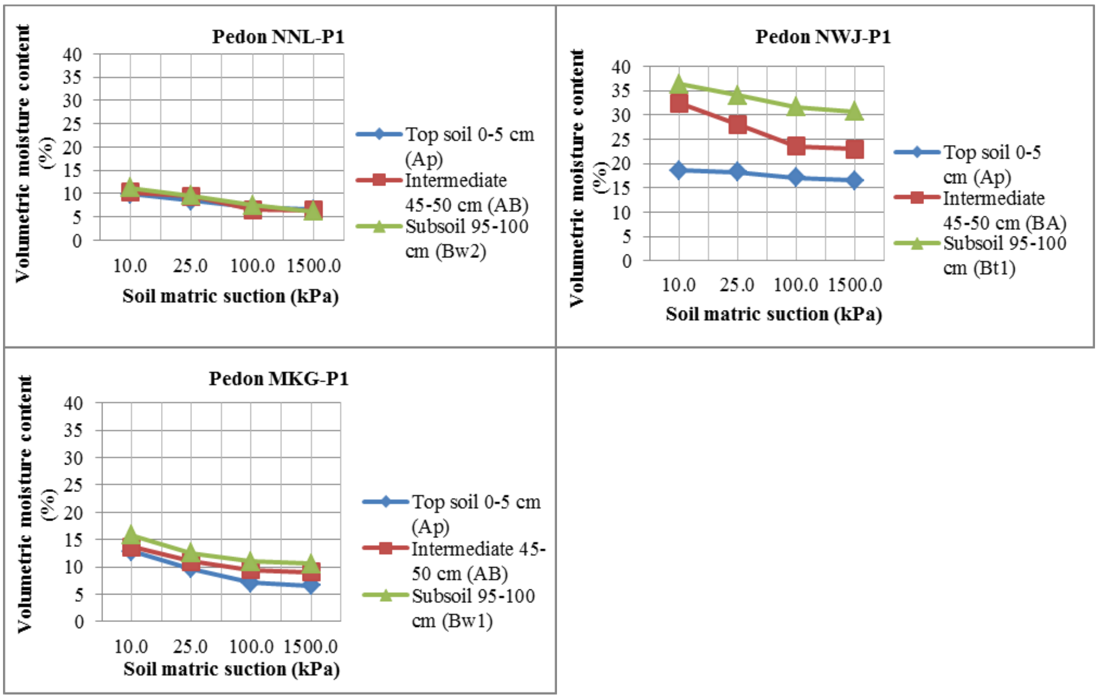

Figure 2.3: Soil moisture characteristic curves of the studied pedons at Nannala, Nawaje and Mikangaula

2.3.3.1 Soil pH and electrical conductivity (EC)

Soil pH plays an important role in determining the solubility and reactivity of soil elements such as Al, Mn and Cd (Peverill *et al*., 1999). According to EuroConsult (1989) and Horneck *et al*. (2011), pedons NWJ-P1 and MKG-P1 are rated as being medium acid to slightly acid with pH ranging between 5.91 and 6.35. This pH range being > 5.5 is favourable for the growth of a wide range of crops. The pH values of pedon NNL-P1 range between 4.36 and 4.57 and are rated as extremely acidic to very strongly acidic (Msanya *et al*., 2001). Such low pH values are not favourable for plant growth. Landon (1991) reported that acidic soils with low pH (< 5.5) have a great potential to cause Al, Mn and Fe toxicity, deficiencies of some essential nutrients to plant growth and retardation of microbial activity and decomposition of organic matter. The low pH in this pedon may be attributed to low organic matter through continuous removal of crop residues and burning during farming practices.

Electrical conductivity (EC) is a measure of salinity in the soil. The EC values of all the studied pedons are very low (< 1.7 dS/m). The low EC values throughout the pedons do not pose any problem of crop yield reduction (Msanya *et al*., 2001; APAL, 2017).

Table 2.5: Selected chemical properties of the studied pedons at Nannala, Nawaje and Mikangaula

Pedon	Horizon	pH		EC	OC	OM	TN	C/N	Available P
		H_2O	KCl	(dS/m)		%		ratio	(mg kg^{-1})
NNL-P1	Ap	4.57	3.75	0.03	0.49	0.84	0.04	12	8.71
	AB	4.52	3.75	0.03	0.39	0.67	0.03	13	1.98
	Bw1	4.43	3.75	0.03	0.27	0.47	0.03	9	1.86
	Bw2	4.40	3.79	0.03	0.31	0.53	0.05	6	1.50
	Bw3	4.36	3.74	0.03	0.20	0.34	0.02	10	1.56
NWJ-P1	Ap	6.12	5.37	0.04	1.28	2.21	0.05	26	2.70
	BA	5.95	4.63	0.02	1.26	2.17	0.07	18	1.26
	Bt1	5.88	4.71	0.02	0.66	1.14	0.06	11	0.36
	Bt2	5.93	5.13	0.02	0.45	0.78	0.04	11	0.72
	Bt3	5.97	5.49	0.02	0.49	0.84	0.05	10	0.36
MKG-P1	Ap	6.34	5.44	0.02	0.53	0.91	0.03	18	6.13
	AB	6.35	5.19	0.02	0.20	0.34	0.03	7	3.30
	Bw1	6.18	5.38	0.02	0.22	0.38	0.02	11	2.28
	Bw2	5.91	4.97	0.02	0.31	0.53	0.03	10	1.92
	Bwc	5.98	4.47	0.02	0.16	0.28	0.02	8	1.08

2.3.3.2 Organic carbon (OC), organic matter (OM) total nitrogen (TN) and C/N ratio

Organic carbon (OC) contents in topsoils of the studied pedons ranged from very low to medium (Msanya *et al* 2001) with values of 0.49 to 1.28%, corresponding to 0.84 to 2.21% organic matter (OM) (Table 2.5). Subsoil OC contents ranged from very low to low (0.16 - 0.66%), corresponding to 0.28 - 1.14% OM. Generally the OC content decreases with depth for the three studied soils. According to Ndakidemi and Semoka (2006) and Brady and Weil (2008), OC is a major component of OM and plays a vital role in the plant nutrients such as phosphorus and sulphur, and is the primary source of nitrogen for plant growth.

The values of total nitrogen in the studied pedons ranged from 0.02 - 0.07 (Table 2.5), while the C/N ratios ranged from 7 to 18. This range indicates that the studied surface and subsurface horizons though with a very low total N content (< 0.10%), had C/N ratios ranged within 8 to 20 indicating good to moderate quality of soil organic matter (SOM) for pedons NNL-P1 and MKG-P1. However, topsoil C/N ratio of pedon NWJ-P1 is exceptionally high (>20) indicating poor quality (EuroConsult, 1989), which implies slowdown of decomposition rate by soil microbes; hence low N content in the soil (Ge *et al*., 2013). According to Msanya *et al*. (2003), low N content in the soil requires N fertilizer application for optimal plant growth.

2.3.3.3 Available P

Available phosphorus in the studied pedons ranges from 0.36 mg kg^{-1} to 8.71 mg kg^{-1}, with values decreasing as depth increases (Table 2.5). According to EuroConsult, (1989) and Msanya *et al*. (2001), all the studied soils are rated as low in P contents except for topsoil of pedon NNL-P1 which is rated as medium. Available P of 7.0 mg P kg^{-1} and above is considered optimum below which P-deficiency symptoms are likely to occur in most crops (Landon, 1991; EuroConsult, 1989). Landon (1991) reported that when P is < 15 mg kg^{-1}, response of most crops to P is expected. The low values of P observed in the studied soils could be attributed to the nature of soil parent material, low soil pH <5.8 (particularly for pedon NNL-P1) which would favour reaction with iron (Fe) and aluminium (Al) to inhibit availability of P to plants. Similar P trends were reported in studies done by Balemi and Negisho (2012), Nigussie *et al*. (2013) and Tabi *et al*. (2013).

2.3.3.4 Exchangeable bases, cation exchange capacity (CEC) and base saturation (BS)

The amounts of exchangeable cations namely Ca, Mg, K and Na of the studied pedons are presented in Table 2.6. Ca levels vary among and within pedons with no specific trend.

According to Msanya *et al*. (2001) topsoil Ca levels are rated as high for both pedons NNL-P1 (2.75 cmol (+) kg^{-1} soil) and NWJ-P1 (5.54 cmol (+) kg^{-1} soil) and as medium for pedon MKG-P1 (1.95 cmol (+) kg^{-1} soil). Subsoil Ca levels ranged from 0.65 cmol (+) kg^{-1} soil (low) to 3.45 cmol (+) kg^{-1} soil (high) for pedon NNL-P1; 1.65 cmol (+) kg^{-1} soil (very low) to 2.85 cmol (+) kg^{-1} soil (medium) for pedon NWJ-P1; and from 0.25 cmol (+) kg^{-1} soil (very low) to 2.25 cmol (+) kg^{-1} soil (medium) for pedon MKG-P1.

Topsoil exchangeable Mg levels are low in pedon NNL-P1 while they are medium in pedons NWJ-P1 and MKG-P1. Subsoil Mg levels ranged from medium to high for pedon NWJ-P1 and low to medium for pedon MKG-P1. Exchangeable Mg in pedon NNL-P1 decreases with depth. The relatively low values of exchangeable Mg in the topsoils of this pedon could be due to low leaching losses, washing by runoff and mining by cropping systems (Munishi, 2012; Lü *et al*., 2016). In the case of pedons NWJ-P1 and MKG-P1 exchangeable Mg increases with depth most probably due to leaching of this cation down the pedon.

Topsoil exchangeable K values are rated as low in pedons NNL-P1 and MKG-P1 (respectively 0.05 and 0.20 cmol (+) kg^{-1} soil) and medium for pedon NWJ-P1 (0.49 cmol (+) kg^{-1} soil). Subsoil exchangeable K values for pedon NNL-P1 are very low (0.02 to 0.07 cmol (+) kg^{-1} soil), medium for pedon NWJ-P1 (0.39 to 0.62 cmol (+) kg^{-1} soil) and low to medium for pedon MKG-P1 (0.22 to 0.52 cmol (+) kg^{-1} soil).

Exchangeable Na values range from 0.02 - 0.10 cmol (+) kg^{-1} soil with most of the horizons having < 0.1 cmol (+) kg^{-1} soil which is ranked as very low. This indicates there is no sodicity problem in the three studied soils (EuroConsult, 1989).

Table 2.6: Exchangeable bases and related properties of the studied pedons at Nannala, Nawaje and Mikangaula

Pedons	Horizon	Depth (cm)	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC_{soil}	BS
			cmol (+) kg^{-1}						(%)
NNL-P1	Ap	0 - 25/30	2.75	0.35	0.05	0.03	3.18	7.41	43
	AB	25/30 - 50/55	1.85	0.26	0.06	0.02	2.19	7.18	31
	Bw1	50/55 - 85/88	1.75	0.28	0.02	0.02	2.07	5.39	38
	Bw2	85/88 - 112/115	3.45	0.26	0.07	0.08	3.86	8.86	44
	Bw3	115 - 160+	0.65	0.26	0.02	0.02	0.95	2.24	42
NWJ-P1	Ap	0 - 22/30	5.54	1.88	0.49	0.07	7.98	10.9	73
	BA	22/30 - 52/60	2.85	2.45	0.39	0.08	5.77	8.02	72
	Bt1	52/60 - 80 /100	2.35	2.62	0.56	0.07	5.60	7.60	74
	Bt2	80/100 - 140	1.75	2.85	0.62	0.08	5.30	8.13	65
	Bt3	140 - 200+	1.65	2.60	0.52	0.10	4.87	7.18	68
MKG-P1	Ap	0 - 16/24	1.95	0.51	0.20	0.03	2.69	3.90	69
	AB	16/24 - 45/49	2.25	0.56	0.28	0.03	3.12	4.59	68
	Bw1	45/49 - 103	0.45	1.56	0.22	0.05	2.28	3.42	67
	Bw2	103 - 156	0.25	1.33	0.43	0.05	2.06	3.04	68
	Bwc	156 - 200+	0.45	1.09	0.52	0.05	2.11	3.15	67

Cation exchange capacity (CEC) data are presented in Table 2.6. CEC determines the ability of soil to bind or hold exchangeable cations against leaching (Msanya *et al*., 2001; Olorunfemi *et al*., 2016). The CEC values of the studied pedons range from 3.9 to 10.9 cmol (+) kg^{-1} for topsoils and from 2.24 to 8.86 cmol (+) kg^{-1} for subsoils, respectively. According to Landon (1991), the topsoil and subsoil CEC values are rated as ranging from very low (< 6.0 cmol (+) kg^{-1}) to low (6.0 - 12.0 cmol (+) kg^{-1}). The determination of CEC becomes an important parameter in the soil as it plays an important role in soil fertility. Higher CEC values reflect higher soil fertility (Wiyantoko and Rahmah, 2017).

Base saturation (BS) values of the studied pedons range from 43.0 to 73.0 % and from 31.0 to 74.0 % in topsoils and subsoils, respectively (Table 2.6). According to Landon (1991), BS of < 20% is low, 21 to 60% medium and > 60% high. On the basis of this categorization, pedon NNL-P1 has medium BS while pedons NWJ-P1 and MKG-P1 have high BS. According to FAO (2006), soils having BS<50% are considered as less favourable soils whereas those with BS≥50% are more favourable soils for crops.

2.3.3.5 Cation ratios and nutrient balance in the studied pedons

The availability of nutrients for plant uptake does not depend only on their absolute amounts but also on cation ratios / balance (Kalala *et al*., 2017). In most cases, a good trend is with calcium higher than magnesium, and magnesium higher than potassium (EuroConsult, 1989). Cation ratios in the studied pedons are presented in Table 2.7. The trend Ca>Mg>K (see also Table 2.6) which prevails in the three studied pedons generally indicates a good balance among the cations, hence nutrient availability to plant.

Table 2.7: Cation ratios and nutrient balance in the studied pedons at Nannala, Nawaje and Mikangaula

Profile	Horizons	Depth (cm)	Ca/Mg	Ca/TEB	Mg/K	% (K/TEB)
NNL-P1	Ap	0 - 25/30	7.86	0.86	7.00	1.57
	AB	25/30 - 50/55	7.12	0.84	4.33	2.74
	Bw1	50/55 - 85/88	6.25	0.85	14.00	0.97
	Bw2	85/88 - 112/115	13.27	0.77	0.37	15.59
	Bw3	115 - 160+	2.50	0.68	13.00	2.11
NWJ-P1	Ap	0 - 22/30	2.95	0.69	3.84	6.14
	BA	22/30 - 52/60	1.16	0.49	6.28	6.76
	Bt1	52/60 - 80/100	0.90	0.42	4.68	10.00
	Bt2	80/100 – 140	0.61	0.33	4.60	11.70
	Bt3	140 - 200+	0.63	0.34	5.00	10.68
MKG-P1	Ap	0 - 16/24	3.82	0.72	2.55	7.43
	AB	16/24 - 45/49	4.02	0.72	2.00	8.97
	Bw1	45/49 - 103	0.29	0.20	7.09	9.65
	Bw2	103 -156	0.19	0.12	3.09	20.87
	Bwc	156 - 200+	0.41	0.21	2.10	24.64

The Ca/Mg ratios ranged from 2.50 to 13.27, 0.61 to 2.95 and 0.19 to 4.02 in pedons NNL-P1, NWJ-P1, and MKG-P, respectively. According to Msanya *et al*. (2001), optimum Ca/Mg ratios favourable for most crops ranged from 2 to 4. The Ca/Mg ratios observed in topsoils of the studied pedons are within the optimum range except for pedon NNL-P1 in which they are higher than the favourable level. This high Ca/Mg ratio may limit the uptake of Mg by plants. Landon (1991) reported that availability of Mg and P to plant becomes less as the Ca/Mg ratio exceeds 5:1. The Ca/TEB ratios in the studied pedons ranged from 0.12 to 0.86 (Table 2.7). According to Landon (1991), Ca/TEB ratio which is more than 0.5 may affect the uptake of other bases particularly Mg and /or K. Hence, the topsoil Ca/TEB ratios of the studied pedons are unfavourable.

The Mg/K ratios observed in pedons NNL-P1, NWJ-P1 and MKG-P ranged from 0.37 to 14, 3.84 to 6.28 and 2.10 to 7.09, respectively. Whereas, the topsoil Mg/K ratios of pedons NWJ-P1 and MKG-P1 are within the optimum range of 1 to 4 for nutrient uptake by plants (Landon 1991; Msanya *et al*., 2001), those of pedon NNL-P1 are rated as unfavourable. The percentage (K/TEB) ratios of pedons NWJ-P1 and MKG-P1 are rated as favourable while those of pedon NNL-P1 are unfavourable for nutrient uptake. According to Landon 1991 and Karuma *et al*. (2015), % (K/TEB) ratios above 2% are favourable for most tropical crops.

2.3.4 Soil Classification in the Studied Areas

Field description and laboratory analytical data were used to classify the soils of the study areas according to the USDA Soil Taxonomy (SSS, 2014) and the World Reference Base for Soil Resources (IUSS, 2015). Soil diagnostic horizons, properties and materials used in soil classification are presented in Table 2.8, while Table 2.9 presents the soil names according to the USDA Soil Taxonomy (SSS, 2014) and the FAO World Reference Base for Soil Resources (IUSS, 2015). According to the USDA Soil Taxonomy the main soils of the studied areas are *"Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, isohyperthermic, Typic Dystrustepts" (*pedon NNL-P1*), "Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, isohyperthermic, Typic Argiustolls" (*pedon NWJ-P1*)* and "*Level to rolling,, very deep, loamy, medium acid to slightly acid, isohyperthermic, Typic Haplustepts (*pedon MKG-P1*)* corresponding to *"Dystric Cambisols (Arenic, Ochric)","Luvic Phaeozems (Abruptic, Clayic, Chromic)"* and *"Eutric Chromic Cambisols (Loamic, Ochric)"*, respectively in the WRB.

Table 2.8: Diagnostic features and classification of the studied pedons according to USDA Soil Taxonomy (Soil Survey Staff, 2014)

Pedon	Diagnostic horizon(s)	Other diagnostic features	Order	Suborder	Great group	Subgroup	Family
NNL-P1	Ochric epipedon; Cambic horizon	Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, ustic SMR[≠], isohyperthermic STR[#]	Inceptisols	Ustepts	Dystrustepts	Typic Dystrustepts	***Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, isohyperthermic, Typic Dystrustepts***
NWJ-P1	Mollic epipedon; Argillic horizon	Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, ustic SMR, isohyperthermic STR	Mollisols	Ustolls	Argiustolls	Typic Argiustolls	***Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, isohyperthermic, Typic Argiustolls***
MKG-P1	Ochic epipedon; Cambic horizon	Level to rolling, very deep, loamy, medium acid to slightly acid, ustic SMR, isohyperthermic STR	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	***Level to rolling,, very deep, loamy, medium acid to slightly acid, isohyperthermic, Typic Haplustepts***

[≠]SMR = Soil moisture regime, [#]STR = Soil temperature regime

Table 2.9: Diagnostic horizons and features, and classification of the studied soils according to WRB for Soil Resources (IUSS WORKING GROUP WRB, 2015)

Pedon No.	Diagnostic horizons	Reference Soil Group (RSG) - TIER1	Principal Qualifiers	Supplementary Qualifiers	WRB soil name - TIER 2
NNL-P1	Cambic horizon	Cambisols	Dystric	Arenic, Ochric,	Dystric Cambisols (Arenic, Ochric)
NWJ-P1	Mollic horizon; Argic horizon	Phaeozems	Luvic	Abruptic, Clayic, Chromic	Luvic Phaeozems (Abruptic, Clayic, Chromic)
MKG-P1	Cambic horizon	Cambisols	Chromic, Eutric	Loamic, Ochric	Eutric Chromic Cambisols (Loamic, Ochric)

2.4 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the studied pedons display varying morphological, physical and chemical properties and are likely to behave differently in terms of their use and management. This emphasizes the need to characterize soils before fertilizer recommendations are made. Pedons NNL-P1 (developed from Neogene sandstones) and MKG-P1 (developed from acid metamorphic rocks) have distinctly coarser texture (LS-SCL) than pedon NWJ-P1) (SCL-C) developed from intermediate metamorphic rocks. In view of its finer texture, Pedon NWJ-P1 displays much more favourable moisture retention characteristics than pedons NNL-P1 and MKG-P1. On the basis of their silt/clay ratios, pedons NNL-P1 and MKG-P1 show lower degree of pedogenic development than pedon NWJ-P1. The former pedons have silt/clay ratios >0.2 while the latter has silt/clay ratios <0.2 and pedogenic features notably clay cutans in the subsoil manifesting higher degree of pedogenic development. In terms of OC, the three studied pedons have very low to medium levels while TN levels were low. Pedon NNL-P1 was strongly acid while pedons NWJ-P1 and MKG-P1 were slightly acid. Available P levels of the studied pedons range from low to medium. Pedons NWJ-P1 and MKG-P1 had high BS values and pedon NNL-P1 medium values. Yet, the CEC values were rated as very low to low for the three pedons. Although there seems to be some degree of nutrient balance in the studied pedons, there are also indications of nutrient imbalance e.g. the Ca/TEB ratios of the three studied pedons are unfavourable for plant nutrient uptake; and Mg/K and %(K/TEB) ratios are unfavourable for pedon NNL-P1 in respect of nutrient uptake. Generally, the soils are of low to medium fertility on the basis of levels of N, OM, pH and available P. According to the USDA Soil Taxonomy, pedons NNL-P1 and MKG-P1 classified as Inceptisols while pedon NWJ-P1 classified as Mollisols, corresponding to Cambisols and Phaeozems respectively, in the World reference Base for Soil Resources.

It is recommended that for sustainable cropping on the studied soils, introduction of technologies suitable for rejuvenating soil fertility such as manuring, crop rotation, proper management of crops residues, lengthening of fallow periods, introduction of leguminous (Bambara groundnut, groundnut, cowpeas) cover crops in the farming system and use of fertilizers, particularly non-acidifying types of fertilizers should be adopted. Aluminum toxicity may be a serious problem in pedon NNL-P1 which is strongly acid. This should be corrected by liming the soils to pH >5.5. In addition, or alternatively, OM application can be used to reduce Al toxicity by binding the Al ions into OM complexes.

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CHAPTER THREE

3.0 ASSESSMENT OF SOIL FERTILITY STATUS FOR BAMBARA GROUNDNUT PRODUCTION TANZANIA IN SOUTH-EASTERN

ABSTRACT

Nutrient balance is an essential component of intensive farming. Intensive farming practiced in the agro-ecological zones of Makonde plateau (C2) and Inland plains (E5) of the south eastern Tanzania for many years without proper soil management has led to nutrient depletion. The objective of the study was to assess the soil fertility status of soils in Bambara groundnut growing areas of the south eastern Tanzania. Twenty two farmers' field sites were sampled whereby composite samples of top soil at 0 – 20 cm depth were collected for physical and chemical analysis. Field sampling sites were recorded using digital global position system and mapped. The results indicate that most of the soils in the study areas were sandy loam (64%), loamy sand (27%) and sandy clay loam (9%). About 28% of the soils in the study areas had very low CEC values (< 6 cmol (+) kg^{-1} soil). Soil pH was strongly acidic to moderately acidic (≤ 5.5) and slightly acidic soils (≥ 6.0) in the C2 and E5, respectively. Total N was very low (< 0.1%) and organic carbon was very low to low (< 0.6%). Low levels of available P (<10 mg kg^{-1}) and inadequate S (SO_4-S) levels (< 10 mg kg^{-1}) were observed. The exchangeable K in the C2 was very low to low (< 0.05 cmol (+) kg^{-1}) while E5 had medium K levels. The calcium level of C2 was low to medium (0.2 – 2.5 cmol (+) kg^{-1}) whereas E5 it was medium to high levels of Ca (0.6 – 5.0 cmol (+) kg^{-1}). The exchangeable Mg^+ levels were very low to low (< 0.2 cmol (+) kg^{-1}) and exchangeable Na^+ levels was less than 0.30 cmol (+) kg^{-1} soil which indicate no sodicity problem. Extractable Zn in the soil was < 0.6 mg kg^{-1} with adequate Fe; whereas >30% had inadequate Mn < 5 mg kg^{-1}. The soils data of the study areas indicate low

fertility status especially with respect to N, P, K, S, Mg and Zn, that is needed to improve soil fertility for crop production.

Keywords: Soil fertility, physical and chemical properties, soil fertility management, south eastern Tanzania

3.1 INTRODUCTION

Soil fertility decline is among major constraints affecting agricultural production and livelihoods of the people in south-eastern Tanzania. Continuous farming on the same piece of land is a common practice used by farmers in crop production, without replenishing the soil nutrients removed by crops. Soil fertility can be improved through use of organic materials, animal manures, inorganic fertilizers, lime and crop rotation practices in combination with leguminous crops (Belachew and Abera, 2010). It has been reported that agricultural intensification and expansion of crop cultivation in marginal soils is responsible for lowering the productivity of many soils (Pretty and Bharucha, 2014).

Human activities, including over-cultivation of croplands, shifting cultivation, slashing and burning of crop residues are some of the practices which can cause nutrient decline in the soils, and such activities are widespread particularly in sub Sahara Africa countries (Abdi *et al*., 2013; Maliki *et al*., 2016). Nutrient depletion has been recognized as a constraint that contributes to low food crop production and incomes, thus affecting livelihood in sub-Sahara Africa including Tanzania. Serious land degradation has been observed in many parts of Tanzania, particularly in the semi-arid areas (Dejene *et al*., 1997; Kangalawe, 2012).

In the South Eastern Tanzania, particularly the Makonde plateau and plains, traditional farming practices including clean weeding, removal and burning of crop residues, shortening and elimination of fallow periods have resulted in increased soil nutrient depletion. Dondeyne *et al*. (2001) and Tenga (2006) reported that population pressure and expansion of human settlements has reduced fallow period to less than three years, which led to most farmers practicing seasonal fallows and/or continuous cultivation system. Poor soil management practices including clean weeding, removal and burning of crop residues reduces soil organic matter content, continuous cropping with limited or without fertilizer application leads to nutrient mining and soil fertility degradation (Ngatunga *et al*., 2001a). Most soils in the South Eastern Tanzania are highly weathered with very low soil fertility status, resulting into low crop yields (Bennett *et al*., 1979). Such soils need proper soil fertility management. In these areas, research has addressed soil acidity amelioration (Majule and Omollo 2008), soil erosion control (Achten *et al*., 2008; Kabanza *et al*., 2013), extent of soil acidification due to use of sulphur (Ngatunga *et al*., 2001a), and extent and severity of acidification (Ngatunga *et al*., 2001b), with less attention paid to soil fertility status.

The investigation of the status of soil fertility would provide valuable information that will help to establish appropriate soil fertility management strategies for farmers, extension workers and policy makers in an effort to improve soil fertility and productivity of the study area. Assessing soil fertility is important as the results obtained could also be used as baseline to monitor changes of soil fertility and its productivity due to various interventions. Therefore, this study intended to assess the fertility status of the soil for Bambara groundnut growing areas in south eastern Tanzania.

3.2 MATERIALS AND METHODS

3.2.1 Description of the study area

The study was conducted in Mtwara region known to be a potential area for Bambara groundnut production in the south eastern Tanzania. The area is located within longitudes 38^o 03’ and 40^o 30’ E and latitudes 10^o 05’ and 11^o 25’ S, at an altitude range of 110 - 900 m above sea level (Figure 3.1). The area is characterised by a uni-modal rainfall pattern that occurs from December to April. The rainfall distribution is erratic, and often interrupted by a dry spell of one to two weeks at the end of January or at the beginning of February. The mean annual rainfall varies with altitude from 820 mm at around 100 meters above sea level (m.a.s.l.) to 1245 mm at 870 m.a.s.l. The lowest mean monthly temperature is 24.3^{o} C in July and the highest is 27.5^{o} C in December. The mean annual temperature is 26^{o} C in the coastal area and 24^{o} C in the inland area (Dondeyne *et al*., 2003), classified the region/area as equatorial savannah with dry winter (Aw) (Kottek *et al*., 2006).

The area comprises two agro-ecological zones as identified by De Pauw (1984). The zones are:

i) Coastal zone (C2), which comprises the Makonde plateau, characterised by undulating plateau and slightly dissected. The undulating plateau is characterised by a flat topped surface rising gently from the Makonde Dissected Plateau in the east towards a steep scarp slopes facing the western edges. Soils in the plateau are deep, highly weathered, well drained with loamy sand top soils and sandy loam or sandy clay loam sub soils (Bennett *et al.*, 1979). The area covered by the Makonde plateau is about 550,000 ha.

ii) Eastern plateaux and mountain block (E5), found in a slightly dissected, gently undulating plain characterised as a scarp-foot-plain slope toward the west and southwest to Ruvuma valley. There are few isolated hills rising prominently from this plain, with steep or near vertical rock faces. The soils are moderately deep coarse sandy loam with occasionally finer sand clay loam subsoils (Bennett *et al.*, 1979). About 650,000 ha of land is covered by the Inland plains.

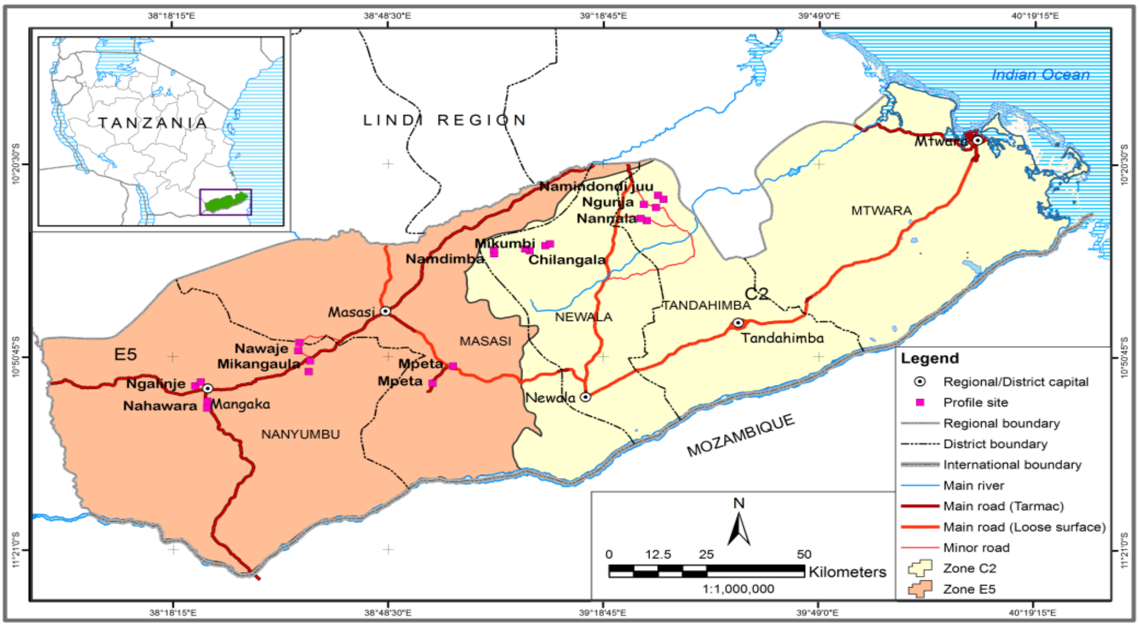

Figure 3.1: Map showing the zonation of south-eastern Tanzania and selected study villages under Bambara production in the study area

3.2.2 Site selection and soil sampling

The selection of the sites was aimed at assessing soil fertility status of the areas for Bambara groundnut production. The selection of the villages was based on dorminat area for Bambara groundnut production. Farmers' selection was based on Bambara groundnut production interest and fields that had no application of manure or fertilizer in the previous year. The fields selected were far apart, with the closest fields within a village being about 1km apart while the farthest were 7 km apart. Soil samples (0 – 20 cm depth) were taken from representative farmers' fields of about 2,000 m^2 to 4,000 m^2 in each village. Composite soil samples were derived from ten soil sub-samples collected randomly using an auger from representative spots and mixed thoroughly. One kg of each composite sample, obtained through quartering procedure, was air dried and sieved through 2 mm for laboratory analysis. A global positioning system (GPS) and clinometer were used to locate the geographical positions and slopes, respectively, of the selected fields.

Table 3.1: Geographical location of the selected villages under Bambara groundnut production in south-eastern Tanzania where soil samples were taken

District	Village	Geographical location/ coordinates	
Tandahimba	Namindondi juu 1	10°25.997’ S	039°27.148’ E
	Namindondi juu 2	10°25.394’ S	039°26.383’ E
	Ngunja 1	10°26.780’ S	039°24.409’ E
	Ngunja2	10°27.274’ S	039°26.110’ E
	Namnala 1	10°29.267’ S	039°24.596’ E
	Namnala 2	10°28.995’ S	039°23.953’ E
Newala	Mikumbi 1	10°33.128’ S	039°10.897’ E
	Mikumbi 2	10°33.009’ S	039°11.248’ E
	Chilangala 1	10°33.854’ S	039°07.891’ E
	Chilangala 2	10°33.793’ S	039°07.760’ E
	Namdimba 1	10°34.077’ S	039°03.398’ E
	Namdimba 2	10°34.382’ S	039°03.149’ E
Nanyumbu	Nawaje 1	10°49.462’ S	038°35.928’ E
	Nawaje 2	10°48.605’ S	038°36.057’ E
	Mikangaula 1	10°51.354’ S	038°37.540’ E
	Mikangaula 2	10°52.723’ S	038°37.359’ E
	Nahawara 1	10°58.746’ S	038°23.076’ E
	Nahawara 2	10°57.674’ S	038°23.134’ E
	Ngalinje 1	10°54.986’ S	038°21.693’ E
	Ngalinje 2	10°54.612’ S	038°22.198’ E
Masasi	Mpeta 1	10°54.883’ S	038°54.761’ E
	Mpeta 2	10°52.168’ S	038°57.643’ E

3.2.3 Laboratory analysis

The physio-chemical analyses were carried out at the laboratories of Mlingano Agricultural Research Institute and Sokoine University of Agriculture. The parameters analysed were particle size distribution, soil pH, organic carbon (OC), total nitrogen (TN), available P, exchangeable bases (Ca, Mg, K and Na), and cation exchange capacity (CEC). Other parameters include extractable sulphur (S), iron (Fe), manganese (Mn) and zinc (Zn). The pH was measured electrometrically in 1:2.5 soil: water suspensions while particle size distribution was determined by the Bouyoucos hydrometer method (Moberg, 2001). Textural classes were determined using the USDA textural classes triangle (IUSS, 2015). Organic carbon was determined by the Walkley-Black wet oxidation method (Nelson and Sommer, 1982) and total nitrogen was determined by the micro-Kjedahl procedure (Bremmer and Mulvaney, 1982). The available P was extracted using the Bray-

1 method (Bray and Kurtz, 1945) and determined by spectrophotometer following colour developed by molybdenum blue method (Murphy and Riley, 1962). The exchangeable bases in the ammonium acetate filtrates were measured by atomic absorption spectrophotometer and cation exchange capacity was determined from NH_4^+ saturated soil residue and the NH_4^+ displaced using 1 M KCl, then determined by Kjeldahl distillation method as for estimation of CEC of the soil (van Ranst *et al.,* 1999). Extractable sulphur (SO_4^{2+}-S) was extracted using calcium monophosphate [$Ca(H_2PO_4)_2.H_2O$], then determined by the turbidimetric method as described by Moberg (2000). Extractable Fe was extracted by acidified ammonium oxalate solution $(COONH_4)_2$ as described by Moberg (2000). The macronutrients (Zn, Fe and Mn) were extracted by diethylene triamine pentacetic acid (DTPA) as described by Lindsay and Norvell (1978). The Fe, Zn and Mn were determined by atomic absorption spectrophotometer. Total exchangeable bases (TEB) were calculated as the sum of exchangeable bases Ca, Mg, K and Na whereas nutrient balance ratio was mathematically calculated using the exchangeable bases. Base saturation parcentage was calculated using the sum of the exchangeable bases divided by the cation exchange capacity (CEC), then multiplied by a hundred.

3.2.4 Statistical Analysis

Correlations showing relationships between pairs of soil parameters were performed using GenStat Release 10.3DE, VSN International Ltd. (Rothamsted Experimental Station) Discovery Edition 4.

3.3 RESULTS AND DISCUSSION

3.3.1 Selected physical properties of the soils

The study area comprised textural classes which are sandy loam, loamy sand and sandy clay loam (Table 3.2). Analytical results of soil samples collected showed that the Makonde plateau (agro-ecological zone C2) and Inland plains (agro-ecological zone E5) had sandy loam soils to the tune of 66.7% and 60%, respectively. Loamy sands covered 16.7% and 40%, respectively, of the soil samples collected in C2 and E5 zones. The Makonde plateau (C2) had 16.7% sandy clay loam whereas Inland plain (E) had no sandy clay loam in the samples collected. Thus, the soils of the study area are predominantly, coarse textured, pointing to a generally low soil fertility status in the area.

Table 3.2: Particle size distribution profiles of soils in the study area

Agroecological zone*	Districts	Soil sampling site	Sand (%)	Silt (%)	Clay (%)	Textural Class
Makonde plateau (C2)	Tandahimba	Namindondi juu 1	86	4	10	LS
		Namindondi juu 2	86	4	10	LS
		Ngunja 1	76	6	18	SL
		Ngunja2	78	4	18	SL
		Namnala 1	80	6	14	SL
		Namnala 2	82	4	14	SL
	Newala	Mikumbi 1	80	4	16	SL
		Mikumbi 2	78	4	18	SL
		Chilangala 1	74	4	22	SCL
		Chilangala 2	76	4	20	SCL
		Namdimba 1	74	8	18	SL
		Namdimba 2	74	8	18	SL
Inland plains (E5)	Nanyumbu	Nawaje 1	80	8	12	SL
		Nawaje 2	76	8	16	SL
		Mikangaula 1	82	8	10	LS
		Mikangaula 2	80	10	10	SL
		Nahawara 1	78	10	12	SL
		Nahawara 2	80	8	12	SL
		Ngalinje 1	82	8	10	LS
		Ngalinje 2	84	6	10	LS
	Masasi	Mpeta 1	86	4	10	LS
		Mpeta 2	82	6	12	SL

Key: LS=Loamy sand, SL=Sandy loam, SCL=Sandy clay loam
*Agroecological zones are shown in figure 3.1

3.3.2 Soil chemical properties

3.3.2.1 Soil pH

The results of soil pH in water (Table 3.3) varied considerably among the sampling sites in the study area ranging from 5.0 to 6.0 and 6.0 to 6.3 for Makonde plateau and Inland plains, respectively. Horneck *et al*. (2011) considered this soil pH range as very strongly acidic to moderate acidic and slightly acidic soils in C2 and E5, respectively. About 92%

of the soil sampled sites in the Makonde plateau had strong acidity to moderate acidity (pH: ≤ 5.5) whereas Inland plains soils had slight acidity (pH: ≥ 6.0). According to Landon (1991), at pH less than 5.5, phosphate ions normally combine with iron and aluminium ions to form insoluble compounds from which P is not readily available to plants.

3.3.2.2 Total Nitrogen and Organic Carbon

Total nitrogen values ranged from 0.04 to 0.08% and 0.02 to 0.05% for Makonde plateau and Inland plains, respectively (Table 3.3). These values for the soil samples collected in the study area are rated by London (1991) as being very low (< 0.1%). More than 90% of the study areas had very low levels of total N, indicating nitrogen deficiency for most crops in the area. Organic carbon (OC) values were also very low (0.14 to 0.79%) for Makonde plateau and 0.20 to 0.65% for Inland plains. About 66.6% of the sites in the Makonde plateau had very low OC whereas 90% of the samples sites in the Inland plain had very low values (< 0.6%) (Euroconsult, 1989). Generally, the study area indicates very low to low values of OC. According to Brady and Weil (2008), OM plays a vital role as store of the plant nutrients including phosphorus and sulphur. Low soil N and organic matter in this area could be attributed to prevailing farming practices mainly slash and burn and removal of crop residues during land preparation that lead to a decrease in the amounts of organic matter in the soils.

3.3.2.3 Available Phosphorus and Sulphur

Table 3.3 presents extractable P (Bray 1) levels in the soils. Extractable P ranged from 1.07 to 6.45 mg kg^{-1} and 5.73 to 8.87 mg kg^{-1} of P for Makonde plateau and Inland plains, respectively. According to Landon (1991), plant response to applied P could be unveiled when soil available P is less than 15 mg kg^{-1} soil.

Table 3.3: Some chemical properties and fertility status of the soils in the Makonde plateau and Inland plains

Agro-ecological zone	Soil sampling site	Soil pH 1:2.5	Ratings	OC (%)	Ratings	Total N (%)	Ratings	Bray – 1 P (mg kg^{-1})	Ratings	Sulphur (mg kg-1)	Ratings
Makonde plateau (C2)	Namindondi juu 1	5.2	mda	0.60	l	0.05	vl	1.07	l	4.86	l
	Namindondi juu 2	5.3	mda	0.27	vl	0.04	vl	1.34	l	10.94	m
	Ngunja 1	5.4	mda	0.37	vl	0.06	vl	2.60	l	3.99	l
	Ngunja 2	5.2	mda	0.14	vl	0.04	vl	2.51	l	13.54	m
	Namnala 1	5.4	mda	0.45	vl	0.04	vl	3.13	l	9.20	m
	Namnala 2	6.0	mda	0.57	vl	0.08	vl	6.45	l	9.20	m
	Mikumbi 1	5.3	mda	0.30	vl	0.05	vl	1.97	l	20.49	h
	Mikumbi 2	5.0	vsta	0.39	vl	0.05	vl	1.79	l	7.47	m
	Chilangala 1	5.0	vsta	0.49	vl	0.05	vl	1.88	l	17.01	m
	Chilangala 2	5.0	vsta	0.60	l	0.05	vl	1.70	l	6.60	m
	Namdimba 1	5.4	mda	0.66	l	0.08	vl	2.96	l	10.07	m
	Namdimba 2	5.3	mda	0.79	l	0.06	vl	2.78	l	6.60	m
Range		**5.0 - 6.0**		**0.14 - 0.79**		**0.04 - 0.08**		**1.07 - 6.45**	l	**3.99 - 20.49**	
Inland plain (E5)	Nawaje 1	6.0	mda	0.45	vl	0.04	vl	8.24	l	3.99	l
	Nawaje 2	6.2	sla	0.28	vl	0.02	vl	6.72	l	6.60	m
	Mikangaula 1	6.1	sla	0.37	Vl	0.03	vl	7.08	l	7.47	m
	Mikangaula 2	6.0	mda	0.65	l	0.04	vl	6.9	l	11.81	m
	Nahawara 1	6.2	sla	0.40	vl	0.05	vl	5.73	l	7.47	m
	Nahawara 2	6.1	sla	0.30	vl	0.03	vl	7.52	l	8.33	m
	Ngalinje 1	6.3	sla	0.20	vl	0.03	vl	8.87	l	3.13	l
	Ngalinje 2	6.3	sla	0.40	vl	0.03	vl	6.54	l	9.20	m
	Mpeta 1	6.2	sla	0.20	vl	0.03	vl	7.79	l	5.73	m
	Mpeta 2	6.0	mda	0.50	vl	0.03	vl	6.99	l	5.73	m
Range		**5.0 -6.3**		**0.20– 0.65**		**0.02– 0.05**		**5.73 - 8.87**		**3.13 - 11.81**	

Key: vsta =very strong acidic, mda = moderate acidic, sla = slightly acidic (Horneck *et al*., 2011), Vl = very low, l = low (Euroconsult, 1989), vl = very low, (Landon, 1991), l=low (Landon, 1991), l = low, m = medium, h = high (Horneck *et al*., 2011)

The present results indicate that the Makonde plateau and the Inland plains soils have low levels of soil available P for the growth of most crops. According to Mhango *et al*. (2008), the critical P level for optimum growth of Bambara groundnut is 10 mg kg^{-1}. This critical level and the lower P levels (Table 3.3) indicate that the soils of the study area have low levels of extractable P for Bambara production, and thus they need supplemental P fertilizer.

Exchangeable S (SO_4-S) levels of the soil ranged from 3.99 to 20.49 mg kg^{-1} and 3.13 to 11.81 mg kg^{-1} for Makonde plateau and Inland plains, respectively (Table 3.3). According to Landon (1991), a level of 6 mg kg^{-1} is critical for SO_4-S, below which response of most tropical crops to S is expected. Mhango *et al*. (2008) reported that critical level of soil S (SO_4-S) for optimal growth of Bambara groundnut is 10 mg kg^{-1}. Based on this classification, over 70 % of soils of the study area had inadequate levels of sulphur (< 10 mg kg^{-1}) hence S containing fertilizers need to be applied for increased Bambara groundnut yields.

3.3.2.4 Exchangeable Calcium, Magnesium, Potassium and Sodium

The values of exchangeable Ca in the Makonde plateau (C2) and Inland plains (E5) (Table 3.4) ranged between 0.45 and 1.98 and 1.13 and 3.54 cmol (+) kg^{-1} soil, for soils of C2 and E5, respectively. Landon (1991) rates the soils of Makonde plateau (C2) as having low to medium (0.2 – 2.5 cmol (+) kg^{-1} soil) and the Inland plain as having medium to high (0.6 – 5.0 cmol (+) kg^{-1} soil) Ca levels, respectively. Horneck *et al*. (2011) reported that calcium deficiency usually occurs on very acidic soils. The data from the study area indicate that 92% of the Makonde plateau (C2) soils are strongly acidic (pH 5.0 – 5.5) whereas Inland plains (E5) had slightly acidic soils. Low pH could dominate in soils developed over sandstone parent material which are low in soluble bases and have coarse texture which facilitates leaching, especially in Makonde plateau (C2**).**

Exchangeable Mg in soils of Makonde plateau (C2) ranged between 0.06 to 0.5 cmol (+) kg^{-1} soil and in soils of Inland plains (E5) 0.20 to 1.01 cmol (+) kg^{-1} soil as presented in Table 3.4. According to Landon (1991) and EuroConsult (1989) Mg values of Makonde plateau were very low to low whereas Inland plains had low to medium levels of Mg. About 58% of the Makonde plateau had very low contents of Mg in soil whereas 60 % of the Inland plains had low Mg levels, hence the need for supplemental Mg to improve plant growth.

Exchangeable Potassium (K) levels of soils samples in the Makonde plateau and Inland plains ranged from 0.02 to 0.09 and 0.02 to 0.39 cmol (+) kg^{-1}, respectively (Table 3.4). According to Landon (1991) the response to K fertilizer is likely when the exchangeable K in clay, loamy and sandy soils is less than 0.2 to 0.4, 0.13 to 0.25 and 0.05 to 0.10 cmol (+) kg^{-1}, respectively. This categorization indicates that soils from the Makonde plateau (C2) were rated as being very low to low (< 0.05) whereas Inland plains (E5) were rated as being medium. These results imply that K fertilizer is required for optimum production of crops in the study area.

For exchangeable sodium the soils had low values (< 0.30 cmol (+) kg^{-1} soil), indicating no sodicity problem in the studied soils (EuroConsult, 1989).

3.3.2.5 Cation exchange capacity and percent base saturation

The cation exchange capacities of soils of Makonde plateau and Inland plains are presented in Table 3.4: they ranged from 1.30 to 3.38 and 2.10 to 5.66 cmol (+) kg^{-1} soil, respectively. According to Brady and Weil (2008), the CEC determines the ability of the soil to bind or hold nutrients against leaching and it is usually influenced by clay mineral and organic matter components. According to Hazelton and Murphy (2007), the CEC of Makonde plateau and Inland plain soils are rated as very low (< 6 cmol (+) kg^{-1} soil). Over

90% of the soils had very low CEC. This could be attributed to the low organic matter content and low clay contents in the soils, which imply that the soils would be marginally suitable for crop production.

The percent base saturation (Table 3.4) of soils of Makonde plateau and Inland plains ranged from 41 to 75% and 50 to 87%, respectively which indicates that the Inland plains are better than Makonde plateau soils for pH as well as for P. According to IUSS (2015), soils having less than 50% base saturation are considered as less favourable soils and those with more than 50% base saturation are considered as favourable soils. It is estimated that 28% of the soils of the study area are categorized as less favourable soils; thus they need appropriate soil management practices to improve the bases for improved crop production.

3.3.2.6 Micronutrients

The DTPA-extractable Zn in the soils of Makonde plateau and Inland plains ranged from 0.06 to 0.67 mg kg^{-1} (Table 3.5). According to Alloway (2008), responses of crops to Zn applications for most crops are expected when extractable Zn is 0.1 to 1.0 mg kg^{-1}, but a critical concentration of 0.6 mg kg^{-1} is considered a desirable limit for a range of crops.

Based on this value, over 90% of the soils of the study area had < 0.6 mg kg^{-1}, suggesting that Bambara groundnut response to Zn application is expected. Extractable Fe values of soils ranged from 12.88 to 76.63 mg kg^{-1}. Sims and Johnson (1991) reported that the critical concentration of Fe for some crops ranges from 2.5 to 5.0 mg kg^{-1}. Based on this critical concentration, all sample sites had adequate Fe for crop production.

Table 3.4: Levels of exchangeable bases and CEC of the soils in the Makonde plateau and Inland plains

Agro-ecological zones (AEZ)	Soil sampling site	Ca	Ratings	Mg	Ratings	K	Ratings	Na	Ratings	CEC	Ratings	BS
		Cmol (+) kg^{-1}										%
Makonde plateau (C2)	Namindondi juu 1	1.08	m	0.22	l	0.04	vl	0.21	l	2.66	vl	50
	Namindondi juu 2	0.61	m	0.07	vl	0.03	v	0.12	l	1.50	vl	47
	Ngunja 1	1.86	m	0.22	l	0.09	l	0.16	l	3.38	vl	64
	Ngunja 2	0.81	m	0.15	vl	0.09	l	0.07	l	2.02	vl	52
	Namnala 1	0.67	m	0.12	vl	0.04	vl	0.12	l	1.73	vl	48
	Namnala 2	1.98	m	0.34	l	0.05	l	0.12	l	3.17	vl	75
	Mikumbi 1	0.56	l	0.11	vl	0.02	vl	0.16	l	1.50	vl	46
	Mikumbi 2	0.45	l	0.06	vl	0.02	vl	0.09	vl	1.30	vl	41
	Chilangala 1	0.53	l	0.12	vl	0.03	vl	0.14	l	1.62	vl	42
	Chilangala 2	0.66	m	0.07	vl	0.04	vl	0.11	l	1.60	vl	48
	Namdimba 1	1.40	m	0.50	l	0.04	vl	0.16	l	3.06	vl	63
	Namdimba 2	1.48	m	0.27	l	0.03	vl	0.09	vl	2.74	vl	65
Range		**0.45 - 1.98**		**0.06 – 0.50**		**0.02 – 0.09**		**0.09 – 0.21**		**1.30 – 3.38**		**41 - 75**
Inland plain (E5)	Nawaje 1	2.58	m	0.78	m	0.24	m	0.21	l	4.58	vl	79
	Nawaje 2	1.54	m	0.39	l	0.14	m	0.09	vl	2.69	vl	77
	Mikangaula 1	1.67	m	0.47	l	0.14	m	0.16	l	3.10	vl	74
	Mikangaula 2	3.54	h	1.01	m	0.39	m	0.07	vl	5.66	l	87
	Nahawara 1	1.91	m	0.52	l	0.14	m	0.18	l	3.30	vl	78
	Nahawara 2	1.35	m	0.20	l	0.15	m	0.05	vl	2.42	vl	70
	Ngalinje 1	1.77	m	0.30	l	0.20	m	0.16	l	3.02	vl	75
	Ngalinje 2	1.56	m	0.27	l	0.18	m	0.14	l	2.69	vl	75
	Mpeta 1	1.14	m	0.20	l	0.12	m	0.04	vl	2.10	vl	70
	Mpeta 2	1.13	m	0.52	l	0.09	l	0.05	vl	2.50	vl	50
Range		**1.13 - 3.54**		**0.20 – 1.01**		**0.02 – 0.39**		**0.04 – 0.21**		**2.10 – 5.66**		**50 - 87**

Key: vl = very low, l = low, m = medium, high for Ca, Mg, K, and Na (Euroconsult, 1989; Landon, 1991), CEC= cation exchange capacity, vl = very low, l = low (Hazelton and Murphy (2007), The extractable Mn values in the study area ranged from 0.72 to 72.38 mg kg^{-1}. Sillanpää (1982) reported that the critical concentration for most crops ranges from 2.0 to 5 mg kg^{-1}, which provide indication that more than 70% of the soils of the study area had high extractable Mn (>5 mg kg^{-1}).

Table 3.5: Levels of selected micronutrients in soils of the study area

Agro-ecological zone	Soil sampling site	Zn	Ratings	Fe	Ratings	Mn	Ratings
				mg kg^{-1}			
Makonde plateau (C2)	Namindondi juu 1	0.11	low	36.63	high	5.72	high
	Namindondi juu 2	0.26	low	49.13	high	2.89	m
	Ngunja 1	0.06	low	24.13	high	11.15	high
	Ngunja 2	0.06	low	27.88	high	5.93	high
	Namnala 1	0.31	low	41.63	high	7.67	high
	Namnala 2	0.21	low	20.38	high	5.93	high
	Mikumbi 1	0.11	low	49.13	high	2.67	m
	Mikumbi 2	0.06	low	65.38	high	0.72	low
	Chilangala 1	0.06	low	46.63	high	1.59	m
	Chilangala 2	0.26	low	76.63	high	1.15	low
	Namdimba 1	0.16	low	40.38	high	4.20	m
	Namdimba 2	0.11	low	35.38	high	3.98	m
Range		**0.06 – 0.26**		**20.13 – 76.63**	high	**0.72 – 11.15**	
					high		
Inland plain (E5)	Nawaje 1	0.62	m	26.63	high	44.13	high
	Nawaje 2	0.11	low	16.63	high	39.78	high
	Mikangaula 1	0.31	low	15.38	high	22.39	high
	Mikangaula 2	0.57	low	16.63	high	35.43	high
	Nahawara 1	0.26	low	17.88	high	28.91	high
	Nahawara 2	0.31	low	17.88	high	44.13	high
	Ngalinje 1	0.67	m	22.88	high	72.39	high
	Ngalinje 2	0.31	low	20.38	high	52.83	high
	Mpeta 1	0.21	low	14.13	high	37.61	high
	Mpeta 2	0.21	low	12.88	high	35.43	high
Range		**0.11 – 0.67**		**12. 88 – 26.63**		**22.39 – 72.39**	

Ratings key: low, medium (Alloway, 2008), high, (Sims and Johnson, 1991), high, m=medium, low (Sillanpää, (1982)

3.3.3 Nutrient balances in the Makonde plateau and Inland plain area

The nutrient ratios of the soil in the study area are presented in Table 3.6. The ratio of Ca/Mg ranged between 2.80 to 9.43 and 2.17 to 6.75 in the Makonde plateau and Inland plain, respectively. According to Landon (1991) and Msanya *et al*. (2001), the optimum range of Ca/Mg ratio for a wide range of crops is 2 to 4. Approximately 60% of the Ca/Mg ratios observed in the soils of Inland plains were within the optimum range while the remaining part as well as in the Makonde plateau 80% of the soils had ratios higher than the favourable levels. Landon (1991) and Hazelton and Murphy (2007) reported that a high ratio of Ca/Mg exceeding 5:1 limits plant availability of Mg and P, implying imbalance of nutrient, thus need to supplement Mg- and P-containing fertilizer.

With regards to Ca/TEB ratios, it ranged from 0.65 to 0.80 for Makonde plateau and 0.63 to 0.77 for Inland plains (Table 3.6). Landon (1991) reported that a Ca/TEB ratio greater than 5 may affect the uptake of other bases, particularly Mg and /or K. The soils in the study area had favourable Ca/TEB ratio of (<5), suggesting that no deficiency of the basic nutrients.

The Mg/K ratios in soils of the Makonde plateau and Inland plains ranged from 1.67 to 12.50 and 1.33 to 5.78, respectively. About 58% of Makonde plateau and 90% of Inland plains had Mg/K ratios which are within the optimum range 1 to 4 for nutrient uptake by plant (Landon, 1991; Msanya *et al*., 2001). The ratios exceeding 1 to 4 as observed in some soils (above) indicate that there is Mg imbalance in those soils. The percentage K/TEB ratio of soils in the study area ranged between 1.60 to 8.57%. According to Karuma *et al*. (2015), the K/TEB ratio favourable for most of tropical crops is above 2%. Over 90% of soils in the study area had K/TEB >2%, suggesting that the area is favourable for most tropical crops. Generally, the nutrient imbalance observed in some areas in the Makonde plateau and Inland plains could negatively affect nutrient availability to plants. Therefore, use of inorganic fertilizers containing these nutrients, and soil amendments such as lime, phosphate rock, and organic manures (crop residues, compost and green manure) is desirable in such areas to improve and balance the lost soil nutrients (Sanginga and Woomer, 2009; Fairhurst, 2012; Uwingabire *et al*., 2016).

Table 3.6: Nutrient balance in the Makonde plateau (C2) and Inland plain (E5) in the South eastern Tanzania

Agro-ecological zone	Soil sampling site	Ca:Mg	Ratings	Ca:TEB	Ratings	Mg:K	Ratings	%(K/TEB)	Ratings
Makonde plateau (C2)	Namindondi juu 1	4.91	high	0.70	good	5.50	high	2.58	f
	Namindondi juu 2	8.71	high	0.73	good	2.33	optimal	3.61	f
	Ngunja 1	8.45	high	0.80	good	2.44	optimal	3.86	f
	Ngunja 2	5.40	high	0.72	good	1.67	optimal	8.04	f
	Namnala 1	5.58	high	0.71	good	3.00	optimal	4.21	f
	Namnala 2	5.82	high	0.80	good	6.80	high	2.01	f
	Mikumbi 1	5.09	high	0.66	good	5.50	high	2.35	f
	Mikumbi 2	7.50	high	0.73	good	3.00	optimal	3.23	f
	Chilangala 1	4.42	optimal	0.65	good	4.00	optimal	3.66	f
	Chilangala 2	9.43	high	0.75	good	1.75	optimal	4.55	f
	Namdimba 1	2.80	optimal	0.67	good	12.50	high	1.90	n.f
	Namdimba 2	5.48	high	0.79	good	9.00	high	1.60	n.f
Range		**2.80 - 9.43**		**0.65 - 0.80**		**1.67 - 12.50**		**1.60 - 8.04**	
Inland plain (E5)	Nawaje 1	3.31	optimal	0.68	good	3.25	optimal	6.30	f
	Nawaje 2	3.50	optimal	0.71	good	2.59	optimal	7.78	f
	Mikangaula 1	3.95	optimal	0.71	good	2.79	optimal	6.48	f
	Mikangaula 2	3.55	optimal	0.68	good	3.36	optimal	5.74	f
	Nahawara 1	5.90	high	0.73	good	1.50	optimal	8.23	f
	Nahawara 2	5.78	high	0.73	good	1.50	optimal	8.37	f
	Ngalinje 1	5.70	high	0.76	good	1.67	optimal	8.00	f
	Ngalinje 2	2.17	optimal	0.63	good	5.78	high	5.03	f
	Mpeta 1	3.67	optimal	0.69	good	3.71	optimal	5.09	f
	Mpeta 2	6.75	high	0.77	good	1.33	optimal	8.57	f
Range		**2.17 - 6.75**		**0.63 - 0.77**		**1.33 - 5.78**		**5.03 - 8.57**	

Ratings Key: optimal, high, good = (Landon, 1991), f = favourable, n.f = not favourable (Karuma *et al*., 2015)

3.3.4 Correlation among some soil chemical properties

Pearson's correlations of some chemical properties of the soils from Makonde plateau and Inland plains, areas where Bambara groundnut is cultivated, are presented in Table 3.7. In the Makonde plateau, the soil available P correlated positively and significantly with Ca (r = 0.67; P = 0.017) and very highly significant with soil pH (r = 0.88; P < 0.001). This finding suggests that as soil pH increases within the limits of the present data, the availability of P also increases, and vice-versa. In most studies, it has been reported that at low pH levels where the soil reaction is classified as acidic (pH < 4.5) phosphate ion is likely to be vulnerable to fixation reactions associated with acid forming cations (e.g. Fe^{3+}, Al^{3+} and H^{+}) and/or Mn^{2+} , which ultimately decrease its availability for plant uptake (Ch'ng *et al*., 2014). Similar finding was reported by Abreu Jr. *et al*. (2003) in indicating correlation between pH and P. Organic carbon was observed to correlate positively and significantly with total N (r = 0.59; P = 0.046).

Table 3.7. Correlations among some chemical properties of the soil in the Makonde plateau

		Measured variables and their corresponding correlations											
		1	2	3	4	5	6	7	8	9	10	11	12
P	(1)	-											
Ca	(2)	0.67*	-										
Fe	(3)	-0.57	- 0.73**	-									
K	(4)	0.23	0.48	- 0.6**	-								
Mg	(5)	0.54	0.76**	-0.56	0.19	-							
Mn	(6)	0.35	0.64*	- 0.77*	0.75**	0.34	-						
Na	(7)	-0.2	0.19	-0.16	-0.1	0.3	0.25	-					
Org. C	(8)	0.22	0.42	0.04	-0.35	0.54	-0.11	0.21	-				
Soil pH	(9)	0.88***	0.74**	-0.7	0.23	0.58*	0.52	0.09	0.14	-			
Sulphur	(10)	-0.06	-0.48	0.07	-0.26	-0.2	-0.39	-0.05	-0.44	-0.1	-		
Total N	(11)	0.66	0.77	-0.37	0.04	0.87***	0.15	0.23	0.59*	0.62*	-0.2	-	
Zn	(12)	0.22	-0.08	0.23	-.0.23	-0.1	-0.01	-0.07	0.16	0.31	-0.14	-0.06	-

Pearson's correlation at 95% confidence level, * signifies P<0.05, ** signifies P<0.01, ***signifies P<0.001.
Key: P = phosphorus, Ca = calcium, Fe = iron, K = potassium, Mn = manganese, Na = sodium, OC = organic carbon, Zn = zinc.

This correlation suggests that decomposition of soil organic matter releases some essential soil nutrients (e.g. N) for plant uptake. The increase of OM in the soil creates a soil nutrient pool for plant nutrients (Azlan *et al.*, 2012). Similar findings were reported by Cao *et al.* (2012), indicating that OC significantly correlated with N in the degraded alpine meadow soils in central Tibet. In the Makonde plateau, Mg was also observed to correlate positively and significantly with pH (r = 0.58; $P = 0.047$) and highly significantly with total N (r = 0.87; $P < 0.001$) (Table 3.7), indicating the aid of the pH on the availability of N and Mg in the soils. Similar findings were reported by Mwango *et al*. (2015) indicating significant correlation of pH with Mg.

Correlations between soil parameters in the Inland plains are presented in Table 3.8. Positive and very highly significant correlation (r = 0.98; $P < 0.001$) was obtained between Ca and K. Calcium also showed similar correlations with magnesium (r = 0.88; $P < 0.001$), significantly with organic carbon (r = 0.68; $P = 0.029$) and zinc (r = 0.67; $P = 0.034$). Apart from manganese and soil pH, which showed insignificant negative correlations with calcium, these findings suggest that calcium is important in increasing availability and/or solubility of most other nutrient elements in these soils and probably for their susceptibility for plant uptake. Calcium weathers relatively quickly and can become unavailable to plants via leaching in highly weathered (mature) soils as compared with other basic cations (Pilbeam and Morley, 2007) increasing the impact of low pH to soil reactions. Fe showed positive and significant correlations with Na (r = 0.73; $P = 0.016$) and Zn (r = 0.72; $P = 0.019$). This finding suggests that increase in Na will impact on soil reaction thereby limiting for solubility of Fe and Zn in soils. Mg correlated positively and significantly with potassium (r = 0.75; $P = 0.013$) and highly significant with organic carbon (r = 0.85; $P = 0.002$). Potassium also correlated positively and significantly with zinc (r = 0.72; $P = 0.02$). Implication of this observation is that having any one of these nutrients will necessitate addition of the others to maintain a good balance and avoid deficiencies.

Table 3.8. Correlations among some chemical properties of the soil in the Inland plains

		Measured variables and their corresponding correlations											
		1	2	3	4	5	6	7	8	9	10	11	12
P	(1)	-											
Ca	(2)	-0.00	-										
Fe	(3)	0.47	0.38	-									
K	(4)	0.13	0.95***	0.37	-								
Mg	(5)	-0.13	0.88***	0.16	0.75*	-							
Mn	(6)	0.63	-0.06	0.6	0.15	-0.32	-						
Na	(7)	0.06	0.29	0.73*	0.13	0.22	0.14	-					
OC	(8)	-0.41	0.68*	-0.06	0.59	0.85**	-0.4	0.01	-				
Soil pH	(9)	0.00	-0.42	0.15	-0.31	-0.70*	0.53	0.18	-0.69*	-			
Sulphur	(10)	-0.64*	0.41	-0.38	0.45	0.31	-0.41	-0.33	0.58	-0.18	-		
Total N	(11)	-0.28	0.54	0.26	0.37	0.54	-0.26	0.45	0.48	-0.25	0.18	-	
Zn	(12)	0.62	0.67*	0.72*	0.72**	0.47	0.52	0.46	0.23	-0.14	-0.17	0.37	-

Pearson's correlation at 95% confidence level, * signifies $P<0.05$, ** signifies $P<0.01$, ***signifies $P<0.001$.
Key: P = phosphorus, Ca = calcium, Fe = iron, K = potassium, Mn = manganese, Na = sodium, OC = organic carbon, Zn = zinc.

3.4 CONCLUSIONS AND RECOMMENDATIONS

The study of soil fertility status in the Makonde plateau and Inland plains lead to the conclusion that soils are acidic, ranging from strongly acidic to slightly acid. Strong soil acidity, especially in the Makonde plateau areas, low pH is likely to limit availability of some nutrients especially the micronutrients. Nitrogen, available P, potassium, calcium and magnesium were also low in these soils.

These alarming extreme situations necessitate immediate attention to replenish decline nutrients in the soil. Therefore, to achieve sustainable crop production in the studied area, use of inorganic fertilizers, liming, use of organic materials (manure, compost etc.) and/or crop rotation should be adopted to alleviate this low soil fertility. Farmers should be trained on utilization of available organic materials and to increase their awareness on the potential of combining inorganic and organic plant nutrient sources for improving soil fertility for cop production.

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CHAPTER FOUR

4.0 SYMBIOTIC N_2–FIXATION OF TWO CONTRASTING BAMBARA GROUNDNUT VARIETIES CULTIVATED ON *CAMBISOLS* AND *PHAEOZEMS* IN SOUTH-EASTERN TANZANIA

ABSTRACT

Legumes are crops commonly with the ability to convert nitrogen gas (N_2) from the atmosphere into the plant available N in the legume-rhizobia symbiotic association. An experiment was conducted to evaluate N_2 fixation by the popular Bambara groundnut landraces grown in the south-eastern Tanzania. Field trials were carried out on classified soils in the villages of Nannala (C*ambisols*) and Nawaje (*Phaeozems*) in 2016. Bambara groundnut improved variety (NalBam 4-13) and a local landrace received phosphorus (P), potassium (K) and nitrogen (N) at rates of 0, 20, 40, and 60 kg P ha^{-1}, 0, 40 and 80 kg K ha^{-1} and 0, 20 and 80 kg N ha^{-1}, respectively, in a split-plot design with three replications. The N-difference method was employed in assessing biological nitrogen fixation (BNF) of the Bambara varieties. Results showed that combinations of P with potassium (K) significantly increased nodulation and N_2 fixation in both Nannala and Nawaje sites. Highest dry matter yields for Nannala and Nawaje sites were 870 and 1407 kg ha^{-1}, respectively whereas highest N_2 fixed was 16.7 kg ha^{-1} at Nannala and 30.18 kg ha^{-1} at Nawaje. The respective combinations of N, P and K found to significantly maximize nodulation and N_2 fixation were P_{40} kg ha^{-1} + K_{40} kg ha^{-1} and P_{40} kg ha^{-1} + K_{80} kg ha^{-1}.

Keywords: *Biological Nitrogen Fixation; food security; plant nutrition; South-Eastern Tanzania*

4.1 INTRODUCTION

Bambara groundnut (*Vigna subterranea* (L.) Verdc), native to Africa, is the third most important of grain legumes after common bean and cowpea in the rural communities in Tanzania. The crop is potentially nutritious for humans and animals; its nuts contain carbohydrates (63%), protein (19%), oil (6.5%), calcium (95.5 mg to 99.0 mg), iron (5.1 mg to 9.0 mg), potassium (11.45 mg to 14.36 mg) and sodium (2.9 mg to 10.6 mg). It is the most popular cultivated grain legume by smallholder farmers in the south-eastern Tanzania where soils are of low fertility (Mponda *et al.*, 2010). Most farmers in this area use local varieties without fertilizer use (Mponda *et al.*, 2010; Mkwachu, 2009). Other farmers rarely cultivate grain legumes in the area that could improve soil fertility like groundnuts (*Archis hypogaea*), pigeon peas (*Cajanus cajan*), green gram (*Vigna radiata*) and cowpeas (*Vigna unguiculata*). The soils in the south-eastern Tanzania being coarse textured (Tables 2.3 and 3.2) have low fertility. Also, they are subjected to continuous cultivation with little or no use of fertilizers while the burning of crop residues after harvest and/or during land preparation is common (Titonell and Giller, 2013).

The R*hizobium* – legume symbiotic association contributes considerable amount of N in cultivated tropical soils but, with variations in rains and temperatures, the rhizobial populations in the soil are highly affected (Yakubu *et al*., 2010). Bambara groundnut, for instance, can fix up to 28 kg N ha^{-1} in cultivated lands in situations with high rains, ideal mean temperature (20 to 28 ^{o}c) and adequate P in soil (Yakubu *et al*., 2010; Toungos *et al*., 2009). Yakubu *et al*. (2010) evaluated the influence of rhizobia inoculation on N_2 fixation by contrasting species of grain legumes in sandy loam soils and found that the amounts of N_2 fixed without inoculation were 25, 36 and 23 kg N ha^{-1} for Bambara groundnut, cowpea and groundnut, respectively.

The contribution of N_2–fixing legumes as a cheaper and more sustainable alternative to synthetic N fertilizers for smallholder farmers in African cropping systems is widely documented (Samago *et al*., 2017; Belane and Dakora, 2010; Naab *et al*., 2009). Ikenganyia *et al*. (2017) observed that access to mineral N makes plants to produce many leaves.

Legumes require phosphorus, starter nitrogen, some potassium, magnesium, and molybdenum for growth, nodulation, nitrogen fixation and seed development (Ikenganyia *et al*., 2017; Agba *et al*., 2016; Unkovich *et al*., 2008; Giller *et al*., 1991). Bambara groundnut is a viable alternative for improvement of soil productivity in areas with low level of nutrient reserves and/or inputs due to its low nutrient requirements, drought tolerance, nutritive and market value, and ability to fix atmospheric nitrogen in erratic climates (Ikenganyia *et al*., 2017; Effa *et al*., 2016; Yakubu *et al*., 2010).

However, in Tanzania, Bambara groundnut rarely receive inorganic N fertilizers and the soils are highly depleted of essential nutrients, and the cropping systems in smallholder farms involve use of low yielding local varieties. Therefore, Bambara groundnuts rely entirely on the naturally available soil nutrients for growth, thereby resulting in lower yields far below potential expectations, and nitrogen fixation by these legumes is low. There is no documented study in Tanzania pertaining to the influence of N, P, and K on N_2 fixation by local and improved varieties of Bambara groundnut when these two are cultivated on *Cambisols* and *Phaeozems*. *Cambisols* occupy about 35.6% of the total area in Tanzania and are soils that are only moderately developed on account of their limited pedogenetic age or because of rejuvenation of the soil material. On the other hand *Phaeozems* occupy about 2.3% of the total area and are the soils that occur in the steppe zone between the dry climates and the humid temperate zone (Deckers *et al*., 2001;

Driessen *et al*., 2001; Nachtergaele *et al*., 2000; Quantin and Spaargaren, 2007). Therefore, the objective of this study was to evaluate N_2 fixation capacities of the popular Bambara groundnut varieties grown in the south-eastern Tanzania and to determine the influence of N, P, and K fertilizers on N_2 fixation and yields of Bambara groundnut.

4.2 MATERIAL AND METHODS

4.2.1 Description of the study area

Experiments for this study were conducted at two sites, namely Nannala and Nawaje, located in Tandahimba and Nanyumbu districts, respectively in Mtwara region. The Nannala site is located at 10° 29.262' S and 39° 24.609' E and Nawaje site at 10° 48.196' S and 38° 36.546' E, with altitude ranging from 200 to 600 meters above sea level (m.a.s.l). The soils were characterized by Tenga *et al*. (2018) as *Dystric Cambisols* and *Luvic Phaeozems* for Nannala and Nawaje, respectively. The rainfall pattern is uni-modal and erratic, often experienced from November to April with a dry spell occurring for one to two weeks at the end of January or early February. The mean annual rainfall recorded during the period of crop growth in the experimental fields was 600 and 943mm for Nannala and Nawaje, respectively (Figure 4.1). The lowest mean monthly temperature is 24.3° C in July and the highest is 27.5° C in December (Dondeyne *et al*., 2003; Kottek *et al*., 2006).

4.2.2 Laboratory analysis

Composite soil samples were randomly collected at the depth of 0 – 20 cm from ten (10) spots using a soil auger, air dried and sieved through in a 2 mm sieve. The soil samples from each experimental site were subjected to routine laboratory analysis following standard procedures (NSS, 1990; Moberg, 2000; Okalebo *et al*., 2002).

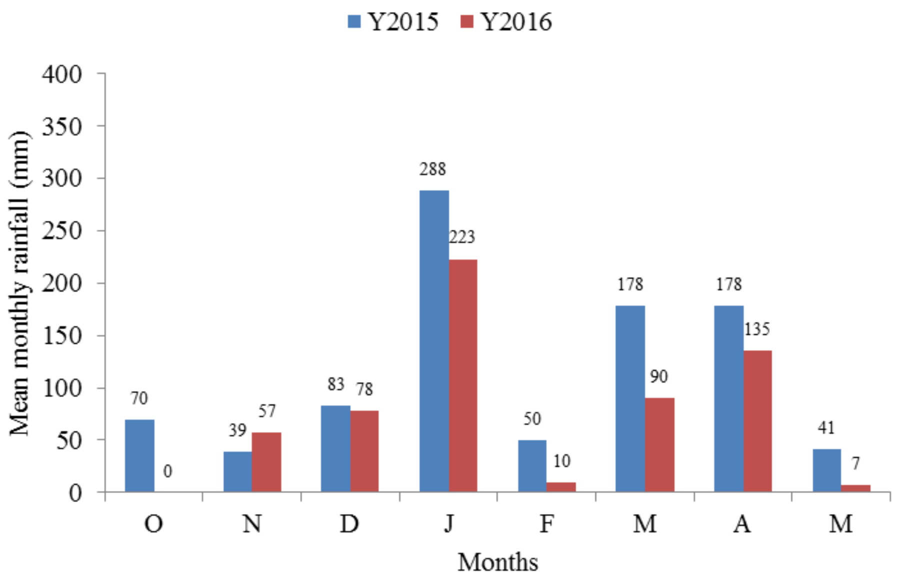

Figure 4.1(a): Rainfall data collected at Luagala Catholic Mission (Nannala) Meteorological Station during 2015 and 2016 rainy seasons

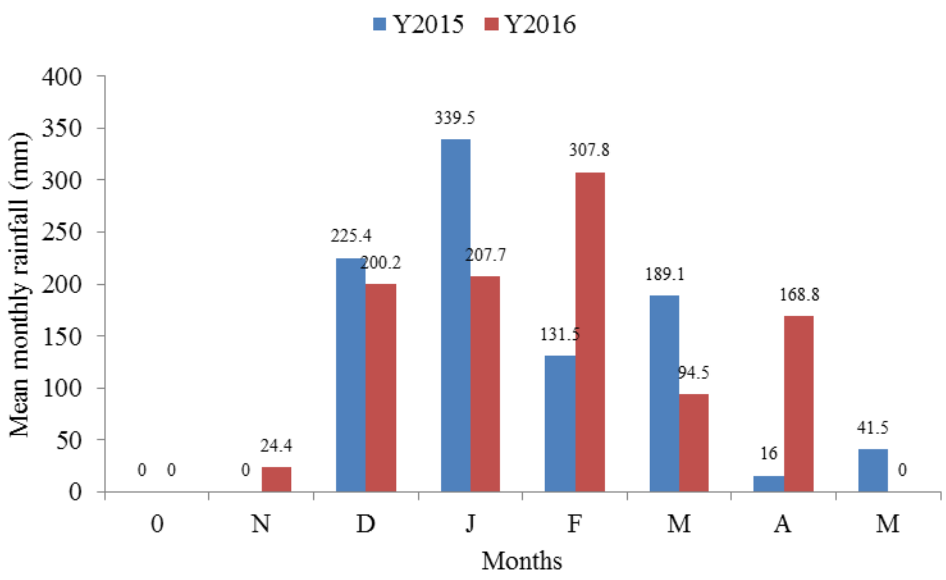

Figure 4.2 (b): Rainfall data collected at Nanyumbu Meteorological Station (Nawaje) during 2015 and 2016 rainy seasons

4.2.3 Experimental Design and Experimentation

The experiment was laid in a split plot design with Bambara groundnut varieties as main plot and fertilizer combinations as subplot. Experimental treatments involved two Bambara groundnut varieties (local and improved NalBam 4-13), eleven (11) fertilizer combinations, as follows:

Treatments	Fertilizer levels
1	$N_0P_0K_0$ (Absolute)
2	$N_0P_0K_{40}$
3	$N_0P_0K_{80}$
4	$N_0P_{20}K_0$
5	$N_0P_{20}K_{40}$
6	$N_0P_{20}K_{80}$
7	$N_0P_{40}K_0$
8	$N_0P_{40}K_{40}$
9	$N_0P_{40}K_{80}$
10	$N_{20}P_0K_0$
11	$N_{80}P_{60}K_{80}$

There was a sole maize (TMV1) plot with no fertilizer application planted adjacent to the above 11 treatments to save as a reference non N_2 fixing crop. The treatments were replicated three times making a total of 66 plots at each site. The treatments were assigned in their respective 11 plots at random. The plot of sole maize (without fertilizer) was a reference crop in the determination of BNF (N_2 fixed) by nitrogen difference method. The field plots measured 3 x 3 m with 7 rows of legumes spaced at (0.5 x 0.2 m) and 4 rows of maize spaced at (0.9 x 0.3 m). The plots were interspaced by 2 m to allow management of crop. Prior to planting, P from Minjingu Hyperphosphate (29% - P_2O_5), N from urea (46% N) and K from muriate of potash (60% K_2O) were applied to give the treatment combinations above and incorporated in the soil. For the treatment with N, a starter of 20 kg N ha^{-1} was applied prior to planting and the other portion applied after four weeks. Three seeds were planted and thinned to one plant per hole.

4.2.4 Data collection

4.2.4.1 Assessing nodulation effectiveness

Destructive sampling at 50% flowering was performed by uprooting five plants from the second line of the plot in the northern direction. Nodules were detached, washed, counted, and dried in oven at 65 ^{O}C to constant weight. Effectiveness of nodulation was assessed by cutting some fresh nodules and observing the colour. Effective nodules were identified by pink, red or brown colours (score of 3 - 5) but nodules with green, white and yellow colours (score of 0 – 2) indicated that the nodules were ineffective (Gwata *et al*., 2003). Effectiveness was scored using a 0 – 5 scale as follows: 4–5 was rated as excellent nodulation with high potential for N_2 fixation, 3–4 as good nodulation with fair potential for N_2 fixation, 2–3 as fair nodulation but N_2 fixation may not be sufficient to supply the N demand of the crop, 0–2 as poor nodulation with little or no N_2 fixation (Peoples *et al.*, 1989).

4.2.4.2 Determination of biological nitrogen fixation

Plant samples were subjected to laboratory analysis and both N concentration and N uptake accumulated by legume and non-legume plants were assessed (Murray *et al*., 2008). The subtraction of total nitrogen of the reference crop (maize) from that of legume (Bambara groundnut) was done to get the amount of N_2 fixed by the legume. The difference found was assumed to be N derived by biological nitrogen fixation (N_2 fixed).

Thus, N_2 fixed = Total N in legume -Total N in reference crop

Total N_2 fixed in plants (kg ha^{-1}) = (% N in plants ×Dry matter weight (kg ha^{-1})/100

4.2.5 Statistical Analyses

To test for the effect of treatments that is varieties of Bambara groundnut, and different levels of N, P and K combinations, two-way ANOVA was performed within a site using GenStat computer software. Bambara varieties were main plots while fertilizer levels were sub-plots. Fertilizer treatments were compared using a post-hoc Duncan's New Multiple Range Test (DNMRT).

4.3 RESULTS AND DISCUSSION

4.3.1 Soil properties of experimental sites

Table 4.1 shows the soil properties of the selected sites. The texture of Nannala soil was coarse texture (sandy loam) and the pH was very strongly acidic while at Nawaje the was sand clay loam with slightly acidic pH. In both sites, the total nitrogen (TN), extractable phosphorus and extrachageable potassium were very low, low and low, respectively. Furthermore, levels of organic carbon (OC), which reflects organic matter contents in the soil was rated very low to low in the two sites. Landon (1991) reported that soil with less than 4% OC is rated as low, as observed in Nannala and Nawaje (Table 4.1).

Other parameters including exchangeable bases and micronutrients such as Fe and Zn were rated according to EuroConsult (1989) and Landon (1991) (Table 4.1). In general, the very low to medium ratings for most of the nutrient elements make these soils to be rated as being lower in fertility status. Sulphur was recorded as high. According to Mhango *et al*. (2008), critical level of soil S (SO_4-S) for optimal growth of Bambara groundnut is 10 mg kg^{-1}. High value of sulphur observed in the two sites is thought to be deposited from sulphur powder applied on cashew nut plants in nearby farms to control powdery mildew. The low levels of nutrients element observed in the soil at both sites call for application of the deficient nutrient in order to optimize Bambara groundnut yields.

Table 4.1: Physiochemical properties of soils at Nannala and Nawaje experimental sites

Parameter	Unit	Nannala		Nawaje	
		Value	**Rating**	**Value**	**Rating**
pH_{water}		5	Very strongly acid	6.3	Slightly acid
Organic carbon	%	0.3	Very low	1.3	Low
Organic matter	%	0.5	Very low	2.2	Low
Total nitrogen	%	0.1	Very low	0.1	Very low
Available phosphorus	mg kg^{-1}	7.4	Low	2.9	Low
Calcium	cmol (+) kg^{-1}	0.9	Medium	5.5	High
Magnesium	cmol (+) kg^{-1}	0.6	Medium	1.7	Medium
Potassium	cmol (+) kg^{-1}	0.1	Low	0.5	Medium
Sodium	cmol (+) kg^{-1}	0.1	Low	0.1	Low
Cation exchange capacity	cmol (+) kg^{-1}	3	Very low	11.3	Low
Sulphur (SO_4-S)	mg kg^{-1}	34.3	High	23.8	High
Iron	mg kg^{-1}	39.6	High	19.6	High
Zinc	mg kg^{-1}	0.23	Very low	0.3	Low
Manganese	mg kg^{-1}	7.2	High	30.8	High
Bulk density	g cm^{-3}	1.5		1.4	
Soil fractions					
Sand	%	82		72	
Silt	%	6		6	
Clay	%	12		22	
Textural class		Sandy loam		Sandy clay loam	

Ratings are based on EuroConsult (1989) and Landon (1991).

4.3.2 Effect of Bambara groundnut variety and fertilizer combination on N_2 fixation and yield at Nannala

The influence of Bambara groundnut varieties and nutrient combination on number of nodule per plant, nodule dry weight, nodule effectiveness, N-fixed and dry matter yield weight are presented in Table 4.2. For the N_2 fixation parameters, the local variety recorded higher value on number of nodules (16) and nodule dry weight (23 g) per plant over the improved variety NalBam 4-13. On the other hand, the improved variety NalBam 4-13 recorded slightly higher, but not significantly different, value of nodule effectiveness. However, the improved variety fixed more N_2, but the dry matter yields of both varieties were statistically similar. Improved variety of Bambara groundnut was developed at Agriculture Research Institute (ARI) from local landraces. Therefore, the improved variety of Bambara groundnut, apparently, may not be very different in terms of nodulation from local landraces, hence similarity in behaviour with regard to N_2 fixation and crop yields. It would be desirable to introduce completely new varieties or more crossing is needed to the existing local ones in order to improve yields and N_2 fixation.

On fertilizer combinations, the number of nodules per plant, nodule dry weight, nodule effectiveness and N-fixed and dry matter yields were maximized at the $N_0P_{40}K_{40}$ treatment. Many other treatments were not significantly different over the control except for $N_0P_{40}K_{40}$. These observations imply that P and K were deficient in these soils, as was also shown in Table 4.1. Hence, to increase yields, application of P and K at $N_0P_{40}K_{40}$ is necessary.

Nodulation and N_2 fixation were generally low (Table 4.2), contrary to other studies that showed higher nodulation (Egbe *et al.*, 2013) and N_2 fixation (Yakubu *et al.*, 2010).

Table 4.2: Effect of Bambara ground variety and fertilizer combination on N_2 fixation and yield at Nannala

Treatments	Nodule number	Nodule dry weight (g)	Nodule effectiveness (%)	N-fixed (kg ha^{-1})	Dry matter yield (kg ha^{-1})
Local	16	23	71	9.5	653
Improved (NalBam 4-13)	13	20	75	11.6	693
LSD$_{(0.05)}$	0.8	2.2	4.4	0.8	61.1
Fertilizer combination					
$N_0P_0K_0$	9d*	15.67d	71.67ab	5.84f	480c
$N_0P_0K_{40}$	11d	20cd	75ab	11.26c	617bc
$N_0P_0K_{80}$	10d	20cd	73.33ab	6.87ef	660b
$N_0P_{20}K_0$	17bc	16.83d	73.33ab	14.07b	690b
$N_0P_{20}K_{40}$	18bc	25.17bc	76.67ab	8.01de	667b
$N_0P_{20}K_{80}$	16c	19.17d	73.33ab	9.67cd	717b
$N_0P_{40}K_0$	19ab	25bc	68.33bc	13.69b	683b
$N_0P_{40}K_{40}$	20a	34a	81.67a	16.77a	870a
$N_0P_{40}K_{80}$	18bc	27b	75ab	11.53c	713b
$N_{20}P_0K_0$	10d	16.33d	71.67ab	9.11d	640b
$N_{80}P_{60}K_{80}$	9.8d	18.5d	60c	9.14d	670b
F pr.	**0.001**	**0.001**	**0.001**	**0.001**	**0.003**
CV%	**10.5**	**20.1**	**12.1**	**15.7**	**18.3**

*Values in the same column bearing similar letters did not differ significantly based on the Duncan's Multiple Range Test at P = 0.05.

It seems that rhizobia population for nodulation of Bambara groundnut are either generally very low in these soils or that they are decimated during drought period preceding the growing season. Kyei-Boahen *et al*. (2017) reported that a considerable population of indigenous *Bradyrhizobium* spp. for legume crop varied from 5.27×10^2 to 1.07×10^3 cells g^{-1} soil for some Mozambique soils, and these are low populations. However, upon inoculation profuse nodulation was observed (Ikenganyia *et al*., 2017; Gomoung *et al.*, 2017) and high level of N_2 fixation obtained (Hajjat and Taherzadeh, 2013). The results showing low nodulation (numbers and weight) in the present study call for a study on rhizobia population trends over the year in these soils. Also, effective rhizobia as observed in the present study soils (Table 4.2) should be isolated, tested and superior ones used to produce inoculants so that Bambara groundnut are inoculated every season. Alternatively, proven effective inoculants should be introduced to maximize N_2 fixation in these areas.

The dry matter yields (Table 4.2) are generally low and this will lead to low grain yields, as low as 285 kg ha^{-1} for these areas as routinely reported (Mponda *et al*., 2010). This may be as a result of the low N_2 fixation presently observed, as well as the generally low soil fertility and inadequate moisture. Also, even in the higher NPK treatment the yields were still low. This could be due to leaching of the applied N as rainfalls were high (Figure 1) as these soils are sandy (Table 4.1). According to Romolemana (1999) Bambara groundnut yield response to NPK of 4 t ha^{-1} were observed, whereas Wamba *et al*. (2010) reported Bambara groundnut respons range to NPK of 4.27 – 7 t ha-^{1} of grain yield.

4.3.3 Effect of Bambara ground variety and fertilizer combination on N_2 fixation and yield at Nawaje

The effect of Bambara groundnut variety and fertilizer combination on nodulation and dry matter yield in Nawaje are presented in Table 4.3. The local variety had significantly higher nodule weight, but N_2 fixation and dry matter yields were higher in the improved variety (NalBam 4-13) (Table 4.3). For the N_2 fixation parameters, the improved variety (NalBam 4-13) recorded lower value on nodule dry weight (24 g) per plant over local variety with similar value (11) on nodule number per plant. The parcent nodule effectiveness of improved variety (NalBam 4-13) was slightly higher, but N_2 fixed was significantly higher over the local variety. However, the dry matter yield of improved (NalBam 4-13) variety was significantly higher compared to that of the local variety. On nutrient combinations, the number of nodule per plant, nodule dry weight and nodule effectiveness were maximized at $N_0P_{40}K_{40}$, and N fixed and dry matter yields were maximized at the $N_0P_{40}K_{80}$ treatment though the yields at $N_0P_{40}K_{40}$ and $N_0P_{40}K_{80}$ were statistically similar. Many treatments on nodulation parameters were not significantly different over the control except for $N_0P_{40}K_{40}$ and $N_0P_{40}K_{80}$.

Nodulation and N_2 fixation by Bambara groundnut in Nawaje are generally low, but significantly higher on fixed N_2 and dry matter yield as compared to Nannala (Tables 4.2 and 4.3). This could be due to different texture, moisture and nutrient retention capacities of soil in Nawaje. It should be noted that in the month of February, there was higher rainfall in Nawaje as compared to that in Nannala. Tenga *et al*. (2018) characterized the texture of the soil as sandy loam for Nannala and sandy clay loam for Nawaje. Higher N_2 fixed and dry matter yield in Nawaje could be due to the sandy clay loam compared to sandy loam at Nannala. De Datta (1981) reported that soils with high clay loam contents are suitable for legumes production because of their moderate capacities to retain plant nutrients and soil moisture. The higher clay contents of soil of Nawaje compared to that of Nannala would further allow the moderate retention of moisture and nutrients on the soils, hence encouraging roots growth and other biological processes in the soils including symbiotic BNF process.

Table 4.3: Effect of Bambara ground variety and fertilizer combination on N_2 fixation and yield at Nawaje

Treatment	Nodule number	Nodule dry weight (mg)	Nodule effectiveness (%)	N-fixed (kg ha^{-1})	Dry matter yield (kg ha^{-1})
Local	11	24	79	16.1	962
Improved (NalBam 4-13)	11	20	81	21.3	1179
LSD$_{(0.05)}$	0.8	1.3	3.7	1.17	46.7
Fertilizer combination					
$N_0P_0K_0$	7d*	13.63e	78.33a-f	8.62f	817e
$N_0P_0K_{40}$	9d	14.47e	83.33abc	11.86d	887de
$N_0P_0K_{80}$	11c	16.77e	80a-f	20.12cd	1177abc
$N_0P_{20}K_0$	11c	31.2b	81.67a-d	19.5cd	1080bcd
$N_0P_{20}K_{40}$	11c	20.63d	85ab	20.97bcd	1153bc
$N_0P_{20}K_{80}$	12c	22.47cd	83.33abc	23.58b	1007cde
$N_0P_{40}K_0$	14b	32.37ab	81.67a-e	21bcd	1033bcde
$N_0P_{40}K_{40}$	17a	35.13a	86.67a	22.11bc	1280ab
$N_0P_{40}K_{80}$	11c	24.07c	75b-f	30.18a	1407a
$N_{20}P_0K_0$	8d	16.93e	73.33c-f	9.44ef	847de
$N_{80}P_{60}K_{80}$	8d	16e	71.67df	18.43d	1093bcd
F pr.	**0.001**	**0.001**	**0.02**	**0.001**	**0.001**
Cv%	**14.8**	**12.3**	**9.5**	**12.5**	**17.7**

*Values in the same column bearing similar letters did not differ significantly based on the Duncan's Multiple Range Test at P = 0.05.

With regards to fertilizer combinations, the increase of P and K on N_2 fixed and dry matter yield in both sites resulted in significantly increased N_2 fixation and dry matter yield (Tables 4.2 and 4.3). This could be due to low extractable P in both sites, addition of which is needed in BNF. The P was very low based on ratings by Landon (1991). Kamanga *et al*. (2010) revealed that P deficiency is often found to limit legume growth and yields depending on the ability of the soil to supply sufficient P. Application K in the soil has been proved to benefit the legume plants as observed by Sangakkara *et al*. (2001) in that K fertilizer under suboptimal moisture conditions increased biomass and helps legume plant to overcome moisture stress and promote shoot growth. This suggests that application of P in combination with K in the soil facilitated nodulation and the functioning of the *Rhizobium* symbiosis to fix more atmospheric N_2. The observations are in agreement with that of Hajjat and Taherzadeh (2013) that P application increased total N uptake in Lentile crop, which is probably due to increase in N_2 fixation. Weisany *et al.*

(2013) reported that inadequate supplies of P on legume-dependent symbiosis make plants to suffer nitrogen deficiency.

Before N_2 fixation is improved much in these sites, farmers may have to resort to fertilizer use to increase yields. However, it was seen (Table 4.2 especially) that yields were still low upon NPK use. This may be because the soils were had low contents of other nutrients in addition to NPK (Table 3.3 and 3.4).

4.4 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the Bambara groundnut varieties were, by and large, similar interms of nodulation and N2 fixation parameters. Therefore, much difference in their performance is not likely to be observed. Use of P and K seems to have had a contribution to increase N_2 fixation. Generally, crop yields on both sites are on the lower side. Data showed that Zn, for example, was low in both sites, although, the Zn situation is more serious in Nannala.

Because of the low contents of P and K in the soils, these nutrients should always be applied for Bambara groundnut production. Additional nutrients like Zn should also be supplied as fertilizer in addition to P and K so as to increase Bamabara groundnut yields.

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CHAPTER FIVE

5.0 EFFECTS OF N, P AND K ON YIELD AND YIELD COMPONENTS OF BAMBARA GROUNDNUT (*Vigna subterranea* (L) verde) IN SOILS OF SOUTH-EASTERN TANZANIA.

ABSTRACT

Macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) are important for Bambara groundnut (*Vigna subterranean* (L.) Verde) production in soils with inherent low fertility status in many sub-Saharan African countries. Most farmers do not use fertilizers even in soils of low fertility, and this leads to low yields. Two Bambara groundnut varieties, a local landrace and an improved variety (NalBam 4-13) and use of inorganic fertilizers were studied in 2015 and 2016 growing seasons. The aim of the study was to determine the optimum rate of P and K on the yield and yield components of Bambara groundnut in the south–eastern Tanzania. A treatment containing N fertilizer was included as a reference treatment. Both tested varieties received four rates of 0, 20, 40, or 60 kg P ha^{-1}, in combination with three rates of 0, 40 or 80 kg K ha^{-1} and 0, 20 or 80 kg N ha^{-1} using a split-plot design with three replications. Results showed that some combination of P with K significantly increased yields and yield components of Bambara groundnut varieties at both Nannala (one season) and Nawaje (in two seasons). Nannala site recorded the highest yield of 552.7 kg ha^{-1} at the combination of P 20 and K 40 kg ha^{-1}, which was not significantly different from that of 20 kg P ha^{-1} (504.8 kg ha^{-1}) in 2015 growing season. Also, the same combination of P at 20 and K 40 kg ha^{-1} gave the highest yield of 734.2 kg ha^{-1}, similar to that at 20 kg P ha^{-1} (711.5 kg ha^{-1}) for Nawaje in the same season. In 2016 growing season at Nawaje site the highest yield (515.4 kg ha^{-1}) was associated with 40 kg P ha^{-1}. No data of yield and yield components was recorded at Nannala site due

to drought during pod formation and termite damage in the 2016 growing season. Generally, the yield components of Nannala and Nawaje in 2015 growing season, and Nawaje in 2016 growing season were significantly different ($P < 0.001$) at both sites and the highest records were observed at similar nutrient combinations. The use of P at the rates of 20 – 40 kg P ha^{-1} was necessary for high yields in the study area.

Keywords: Nitrogen, Phosphorus and Potassium; yield component; food security; soil fertility; south-eastern Tanzania

5.1 INTRODUCTION

Bambara groundnut (*Vigna subterranean* (L.) Verdc) is one of the most valuable grain legume grown mainly by subsistence farmers in the sub-Saharan Africa countries (Hillocks *et al.*, 2012). This crop serves the subsistence farmers as food and cash crop for their livelihoods. Tanzania is among the sub-Saharan countries that produce Bambara groundnuts largely in the semi-arid parts, including central, western and south-eastern regions, and in the relatively wetter areas of Lake Victoria (Marandu and Ntundu, 1995). This grain legume is considered as a food security crop due to its adaptation to poor soils and tolerance to drought (Mkandawire, 2007; Mwangwela *et al.*, 2012). Hauze *et al*. (2016) reported that Bambara groundnut is best grown in well drained soil with pH 5.0 – 6.5 and temperature range of 20 to 28°C, with optimal rainfall ranging between 600 – 750 mm per annum, but higher yields are obtained when rainfall is higher.

Smallholder farmers in south-eastern Tanzania cultivate the crop in acidic soils with inherent low soil fertility and erratic rainfalls (Dondeyne *et al*., 2001). Through its cultivation, large amount of nutrients from the soil are removed, without replenishment, and this leads to further decrease in low soil fertility (Tully *et al*., 2015; Reynolds *et al*., 2015; Majule and Omollo, 2008). According to Mponda *et al*. (2010), the limiting factors of Bambara groundnut yield in the south-eastern Tanzania include insect pests and poor agronomic practices and low soil fertility. Mponda *et al*. (2010) also reported that average grain yields of Bambara groundnut from smallholder farmers in the south-eastern zone (SEZ) range between 147 and 287 kg ha^{-1}, much lower than the potential yields of 2,200 kg ha^{-1} (Collinson *et al.* 2000). According to Ngatunga *et al*. (2001a) and Dondeyne *et al.* (2003), soils of south-eastern Tanzania had very low levels of N (< 0.11%), P (Bray–1) (< 15 mg kg-1) and K (< 0.44 cmol (+) kg-1), which in turn contribute to low crop yields.

For high crop yields, application of nutrients such as nitrogen, phosphorus and potassium is necessary for maintaining crop growth and improving yield. Nweke and Emeh (2013) reported that adequate supply of organic or mineral fertilizer to crop produced desirable yield. Application of N containing fertilizer improved general plant growth (Toungos *et al*. (2010), whereas P application enhances flower initiation, seed and fruit development (Ndakidemi and Dakora, 2007). Adequate supply of potassium during the growth period improved plant water relations and photosynthesis (Garg *et al.* 2005).

Many research activities were conducted on the influence of mineral fertilizer on Bambara groundnut and cowpea yields and yield components (Nkaa *et al*., 2016; Effa *et al*., 2016; Jakusko and Dakato, 2015; Yakubu *et al*., 2010). The use of mineral fertilizers for improving Bambara groundnut in Tanzania has rarely been practiced. Few studies have been conducted on Bambara groundnuts in the SEZ and hence the need for this work. This study was conducted to determine the response of Bambara groundnut to different rates of N, P and K and to determine the optimum levels for enhanced crop productivity in the study area.

5.2 MATERIALS AND METHODS

5.2.1 Description of the study area

The study was conducted at two sites, namely Nannala and Nawaje, located in Tandahimba and Nanyumbu districts, respectively, in Mtwara region. Nannala site is located at 10° 29.262' S and 39° 24.609' E and Nawaje site at 10° 48.196' S and 38° 36.546' E, with an altitude ranging from 200 to 600 meter above sea level (m.a.s.l). The rainfall pattern is uni-modal and erratic, often experienced from November to April with a dry spell occurring for one to two weeks at the end of January or early February towards March. The mean annual rainfall recorded in the experimental fields in 2015 and 2016 growing seasons was 600 and 943 mm for Nannala and Nawaje, respectively (as in figures 4.1a and 4.1b). The lowest mean monthly temperature is 24.3° C in July and the highest is 27.5° C in December (Ngatunga, *et al*., 2001b; Kottek *et al*., 2006).

5.2.2 Laboratory analysis

Composite soil samples were randomly collected from ten (10) spots using a soil auger at the depth of 0–20 cm, air dried and sieved through in a 2 mm sieve. Composite soil samples from each experimental site were subjected to routine laboratory analysis following standard procedures (NSS, 1990; Moberg, 2000; Okalebo *et al*, 2002).

5.2.3 Experimental Design

The experiment was laid in a split plot design with Bambara groundnut varieties as main plots and fertilizer combinations as subplots. Two varieties of Bambara groundnut varities (local and improved NalBam 4-13) and eleven (11) fertilizer combinations were involved as experimental treatments. An N fertilizer treatment served as reference. The treatments were replicated three times making 11 treatments per variety and a total of 66 plots at each site. Other detailed descriptions are described in section 4.2.3 (Chapter four),

5.2.4 Data collection

5.2.4.1 Determination of yield attributes

Five plant samples were taken randomly at harvest and carefully dug out from the net plots of 5.6 m^2. The pods were detached from the plants (Haulm) and counted. Air dried pods were weighed and shelled to recover seeds. The total number of pods from five plants was divided by five and recorded as number of pods per plant. Also, similar calculation was made for pod dry weight and seed grain. One hundred (100) seeds obtained from grain yield (section 5.2.4.2) were counted from each treatment and weighed separately.

5.2.4.2 Determination of grain yield

The pods from the net plot of 5.6 m^2 were harvested and detached from the plants. All the pods were air dried and shelled to recover the seeds. The seeds obtained from the net plots were weighed. The total weight of seeds obtained from net plot in each treatment was converted to kg ha^{-1}.

5.2.5 Statistical Analyses

The data on yields and yield attributes within a site were analysed for variance using GenStat computer software. Bambara varieties were main plots while fertilizer levels were sub-plots. The treatment means were compared using Duncan's New Multiple Range Test (DNMRT) at the 5% level of significance.

5.3 RESULTS AND DISCUSSION

5.3.1 Soil properties of experimental sites

Discussion of data on soil properties was presented in section 4.3.1 (Table 4.1), which showed that these soils were of low fertility as shown by low levels of pH, total nitrogen

(TN), organic carbon (OC) extractable phosphorus, extractable potassium and sulphur (SO_4-S), Fe and Zn.

5.3.2 Effect of Bambara groundnut varieties and fertilizer combinations on Bambara groundnut yields and yield components in Nannala

Table 5.1 presents the effect of local and improved (NalBam 4-13) varieties of Bambara groundnut and nutrient combinations on the number of pods, pod dry yield and grain yields.

Table 5.1. Mean values main effect of fertilizer combinations and Bambara ground varieties on yield component and grain yield at Nannala 2015.

Treatments	**No. of pod/plant**	**Pod dry weight (g)**	**Seed grain weight (g)**	**100 seed grain weight (g)**	**Grain seed yield (kg ha^{-1})**
Local	24	13	11	47.5	424
Improved (NalBam 4-13)	29	15	12	47.3	407
$LSD_{(0.05)}$	3.7	1.2	0.7	2.15	32.4
Fertilizer combination					
$N_0P_0K_0$	20f	10.39e	10.08d	44.11c	331.7d
$N_0P_0K_{40}$	257bcd	14.68bc	11.84abc	45.28c	394.2bcd
$N_0P_0K_{80}$	24cde	13.95bcd	10.94bcd	47.09abc	337.9d
$N_0P_{20}K_0$	29b	13.22b-e	13.09a	48.39abc	504.8ab
$N_0P_{20}K_{40}$	27bc	14.81bc	12.34ab	51.2ab	552.7a
$N_0P_{20}K_{80}$	28b	16.14ab	12.32ab	46.77abc	482.4abc
$N_0P_{40}K_0$	33a	18.29a	12.7ab	51.9a	404.8bcd
$N_0P_{40}K_{40}$	36a	15.82ab	13.27a	49.53abc	461.4a-d
$N_0P_{40}K_{80}$	29b	14.55bc	11.19bcd	45.91bc	412.7bcd
$N_{20}P_0K_0$	23def	11.21de	10.14cd	46.87abc	354.8cd
$N_{80}P_{60}K_{80}$	20ef	11.74cde	7.87e	44.42c	335.9d
F pr.	**0.001**	**0.001**	**0.001**	**0.04**	**0.001**
CV%	**11.8**	**17.1**	**11.9**	**9.1**	**15.7**

While the number of pods and pod dry yield and seed weights of the improved variety were significantly higher than in the local variety, the grain yields per hectare were not. The means of yield components were significantly ($P<0.001$) influenced by fertilizer, over the control.

The similarity of grain yields between the local and improved varieties shows that these varieties are not very different, as the improved one was derived from the local ones. The peaking of grain yields at $N_0P_{20}K_{40}$ may imply that higher rates of P may not be necessary to maximize grain yields and this would be more affordable to farmers. These results are similar to those by Akombo and Asema, (2013) in Yandev, Nigeria who found yield to peak at 20 kg P ha^{-1} and 40 kg K ha^{-1}. However, due to the low level of P in the soil (Table 4.1) and the overall low grain yields, P application should always be considered, but K also should always be considered in Nannala site.

5.3.3 Effect of Bambara groundnut varieties and fertilizer combinations on Bambara groundnut yields and yield components in Nawaje

Table 5.2 shows the effects of varieties and nutrient combinations on Bambara groundnut yields and yield components at Nawaje in 2015. The yield components at Nawaje were significantly higher in the improved variety as compared to those in the local variety (Table 5.2) due to better soil condition at Nawaje. However, the opposite was observed in terms of the grain yields. The trend of grain yields in treatments $N_0P_{20}K_0$ and $N_0P_{20}K_{40}$ was similar to that in Nannala (Table 5.1), though at Nannala the difference was not statistically ($P = 0.05$) significant. The trend of higher grain yield at Nawaje was in conformity with higher biomass yields at this site as compared to those at Nannala (Chapter 4). This may be related to relatively higher N_2 fixation at Nawaje as compared to those at Nannala.

In the fertilizer treatments, highest yields of 734.2 kg ha^{-1} were recorded in the $N_0P_{20}K_{40}$ treatment, though there were other treatments with statistically similar yields (Table 5.2). The other nutrient treatments were not significantly different with control except for $N_0P_{20}K_{40}$ and $N_0P_{20}K_0$ at both sites. In general, as already stated above, the yields of

Bambara groundnut of Nawaje site were slightly higher than those of Nannala site. This could be due to site characteristics, with sandy loam in Nannala and sandy clay loam in Nawaje. With sandy loam soil, more leaching of nutrients and low moisture retention could occur during high rainfall events as compared to sandy clay loam in which leaching could be moderate due to high clay content, therefore providing higher moisture retention. Brady and Weil (2008) reported that soil with high amounts clay have great ability to retain moisture and nutrients in the soil for the growth and development of the plant as compared to more sandy soils.

Table 5.2: Mean values main effect of fertilizer combinations and Bambara ground varieties on yield component and grain yield at Nawaje 2015.

Treatments	No. of pod/plant	Pod dry weight (g)	Seed grain weight (g)	100 seed grain weight (g)	Grain seed yield (kg ha^{-1})
Local	29	14	13	45	633.5
Improved (NalBam 4-13)	30	19	16	57	562.4
LSD$_{(0.05)}$	1.2	1.4	0.9	2.13	55.6
Fertilizer combination					
$N_0P_0K_0$	22d	14.1c	11.95d	48.24cd	391.9e
$N_0P_0K_{40}$	28c	14.93bc	13.4cd	50.5abc	619.1a-d
$N_0P_0K_{80}$	29c	16.41bc	14.7bc	51.35abc	489.6de
$N_0P_{20}K_0$	35a	17.34bc	15.87ab	52.74abc	711.5a
$N_0P_{20}K_{40}$	29c	15.86bc	14.22bcd	52.76abc	734.2a
$N_0P_{20}K_{80}$	30bc	16.12bc	14.28bcd	51.86abc	617.4a-d
$N_0P_{40}K_0$	34a	23.62a	17.22a	55.1a8	652.6ab
$N_0P_{40}K_{40}$	32ab	18.56b	17.08a	54.92ab	676.9ab
$N_0P_{40}K_{80}$	31bc	14.78c	12.5cd	51.36abc	643abc
$N_{20}P_0K_0$	28c	14.31c	12.98cd	49.24bcd	500.8cde
$N_{80}P_{60}K_{80}$	29c	15.52bc	13.75bcd	44.33d	540.8bcd
F pr.	**0.001**	**0.001**	**0.001**	**0.005**	**0.001**
CV%	**8.4**	**16.6**	**12.8**	**8.4**	**18.7**

The nutrient combinations of $N_0P_{20}K_{40}$ and $N_0P_{20}K_0$ had statistically similar grain yields and yield components for both sites (Tables 5.1 and 5.2). This implies that K addition may not be necessary at present. Nkaa *et al*. (2014) revealed that P was necessary for growth and seed development and, most especially, in the nitrogen fixation process. This finding tallied with that of Hasan and Ismail (2016) and Tongous *et al*. (2010) who reported that application of P at 82.5 kg ha^{-1} and 60 kg ha^{-1}, respectively, increased yield components of groundnut. Similarly, these results were confirmed by Ikenganyia *et al*. (2017) who reported that 75 kg P ha^{-1} as SSP gave high number of pods and yields of Bambara groundnut in south east Enugu in Nigeria.

The results of effect of varieties and nutrient rates on yield attributes of Bambara groundnut at Nawaje in the 2016 growing season are presented in Table 5.3. In the 2016 rainy season, no harvests were obtained at Nannala site due to drought. The trends of yield components over the two growing seasons of 2015 and 2016 at Nawaje showed much variability between seasons and the nutrient combinations applied.

Table 5.3. Mean values main effect of fertilizer combinations and Bambara ground varieties on yield component and grain yield at Nawaje 2016.

Treatments	No. of pod/plant	No. of unformed pod/plant	Pod dry weight (g)	Seed grain weight (g)	100 seed grain weight (g)	Grain seed yield (kg ha-1)
Local	10	5	5	4	45.7	291.7
Improved (NalBam 4-13)	12	6	7	5	51.3	423.7
$LSD_{(0.05)}$	0.8	0.5	0.7	0.4	1.68	23.96
Fertilizer combination						
$N_0P_0K_0$	9f	4c	4.398d	3.12d	44.86e	255.4f
$N_0P_0K_{40}$	9ef	5bc	5.14cd	4.36bc	47.56b-e	324cde
$N_0P_0K_{80}$	9def	5abc	6.32bcd	5.08ab	47.06cde	317.3def
$N_0P_{20}K_0$	14ab	5bc	6.627bc	4.11bcd	51.84ab	315.5def
$N_0P_{20}K_{40}$	13bc	5bc	7.087b	4.58bc	49.74bcd	409b
$N_0P_{20}K_{80}$	11cd	5bc	4.897cd	4.36bc	50.19abc	380.1bc
$N_0P_{40}K_0$	11cd	6a	9.01a	5.79a	54.16a	515.4a
$N_0P_{40}K_{40}$	15a	6a	7.987ab	5.90a	49.29b-e	510.1a
$N_0P_{40}K_{80}$	11cde	5ab	6.318bcd	3.56cd	47.71b-e	347.4cd
$N_{20}P_0K_0$	11c-f	5bc	4.453d	4.32bc	45.75cde	263.6ef
$N_{80}P_{60}K_{80}$	10def	5bc	4.683cd	4.01bcd	45.35de	296def
F pr.	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
CV%	**14.3**	**17.7**	**24.7**	**18.3**	**7**	**13.5**

The rainfall data on Figures 1a and 1b showed that in March 2016, the average rainfall was less than of that received in the previous year. Normally, the month of March is the period of pod formation of Bambara groundnut in south eastern Tanzania. Since there was inadequate rainfall in March, most of the harvested pods were empty and some had less number of seeds per plant. This could be due to abortion of newly formed seeds due to moisture stress in March 2016.

Similar findings were reported by Vurayai *et al*. (2011). Thus, in the 2016 growing season, the yields and yield components were lower compared to 2015 in Nawaje. This observation is similar to observation made by Chibarabada *et al*. (2015); Mabhaudhi and Modi (2013) and Madukwe *et al*. (2011) who reported that Bambara groundnut has the ability to recover from water stress and was capable of producing some yields under limited water conditions. In general, it should be noted that the grain yield reached a peak at the rate of 40 kg P ha-^{1}, demonstrating the importance of P in increasing Bambara groundnut productivity.

5.4 CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from the data that P has positive impact on increased yields and yield components of Bambara groundnut. The improved variety appeared to be more suited for Nawaje than to Nannala. For the outcome of the tested nutrient combination rates, it was concluded that the use of P at the rates 20 - 40 kg P ha^{-1} recorded the highest yields in the study area.

From the results obtained herein, it is recommende that P should be applied at rate of 20 – 40 kg P ha^{-1} in all areas with P deficiency. Further, evaluation of the need for K and other limiting nutrients like Zn should be done to get a clear picture of their contribution in increasing Bambara groundnut productivity. Since moisture is also a constraint, moisture conservation practices should be evaluated to establish their role in enhancing Bambara groundnut productivity.

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CHAPTER SIX

6.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 General conclusions

From the results obtained in the present study the following conclusions were made:

i) Two pedons at Nannala-P1 and Mikangaula-P1 were classified as Dystrustepts and Haplustepts, respectively, correlating to Cambisols in WRB whereas the one pedon at Nawaje-P1 was classified as Argiustolls corresponding to Phaeozems in WRB. All soils at the three sites have properties that are recommended for Bambara groundnut production.

ii) Soil N, P, K, S, Mg and Zn were deficient in the Bambara growing areas (Makonde plateau and Inland plains) in south-eastern zone (SEZ) of Tanzania. The extent of the deficiency was as follows: N (>90% of the soils analysed), P (>90%), K (>80%), S (>70%), Mg (>90%) and Zn (>90%).

iii) Phosphorus is necessary for increasing N_2 fixation of Bambara groundnut varieties.

iv) Phosphorus application is crucial for achieving high yield in the south-eastern zone of Tanzania.

6.2 Recommendations emanating from the current results

Based on the results of the present research, it is recommended that:

i) N, P, K, S, Mg and Zn, need proper management to improve soil fertility for crop production. This can also be achieved through proper management of crop residues instead of burning as is currently the practice in those areas

ii) Application of P fertilizer at the rate of 20 – 40 kg P ha^{-1} is recommended for Bambara groundnut growing areas in the SEZ with P deficiency so as to improve Bambara groundnut yields. This rate conforms to the existing P recommendation in those areas.

5.3 Recommendation for Further Research

The following are recommendation for further research:

i) Further research is needed to evaluate K and other limiting nutrients like Zn to get a clear picture of their contributions in increasing Bambara groundnut productivity.

ii) Since moisture is also a constraint, moisture conservation practices should be evaluated to establish their role in enhancing Bambara groundnut productivity.

iii) Further study is needed determine the rhizobia population trends, effective rhizobia in these soils should be isolated, tested and superior ones should be used to produce inoculants so that Bambara groundnut are inoculated every season. Alternatively, proven effective inoculants should be introduced to maximize N_2 fixation in these areas.

iv) There is need to undertake research on the economic viability of using P fertilizer on Bambara groundnut in these areas.