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SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF CROP AND SOIL SCIENCES

ON-FARM ASSESSMENT OF PHYSICO-CHEMICAL PROPERTIES OF AN ARENOSOL UNDER APPLICATION OF MINERAL FERTILIZERS AND THEIR IMPACT ON THE YIELD OF MILLET IN THE SAHELIAN ZONE OF NIGER

BY

MAMAN GARBA

(MSc Physical Land Resources)

September, 2014

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DOCTOR OF PHILOSOPHY

IN

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DECLARATION

I hereby declare that this submission is my own work toward the PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Poor soil fertility is a major threat to crop production and rural livelihoods in Niger where resource-poor farmers mostly rely for their subsistence. Field investigations were carried out over 2012 and 2013 seasons to assess changes in selected soil physico-chemical properties of a Sahelian sandy soil (Arenosol) and their impacts on water and phosphorus bioavailability and yield of pearl millet. Treatments were selected from an on-going 14 year-old on-farm experiment on soil fertility restoration technologies carried out at Karabédji, Niger. The treatments consisted of four rates of fertilizer application viz. (i) control or farmer practice, (ii) Di-ammonium Phosphate (DAP) and (iii) NPK 15-15-15 both at 4 kg P per ha and (iv) NPK 15-15-15 + Tahoua Rock Phosphate (TRP) and two farmer management levels (top and bottom farm types). Results showed no significant ($P > 0.05$) influence of fertilizer rates and farm type on most of the soil physical properties measured. However, the difference in farm by farm type accounted for most of the variability observed in air capacity, structural stability and plant available water whereas no such effect was observed with macro-porosity. Fertilizer application rates and farm type interacted significantly ($P < 0.05$) to affect soil structural stability and this was higher in top farm than in bottom farm type. Soil physical quality index (S) varied with depth and the critical values set for sandy soils by Dexter matched the Sahelian Arenosol. Moreover, significant positive relationship ($R^2 = 0.24$, $P < 0.05$) was found between stability of aggregate under water drop effects and soil physical quality index. Plant available water changed with fertilizer application rates, farm type and depth. Higher plant available water was recorded in the fertilizer-treated soils than the control and on top farm than in the bottom farm by farm type and soil depth. Total N, available phosphorus and exchangeable potassium were generally low and were not influenced

much by the treatments on both farm types. However, higher exchangeable K values were recorded at the beginning than at the end of the season and higher values were recorded on top farms than on bottom farm types. Farm by farm type influenced the observed variability in exchangeable potassium. Millet leaf P concentration was more influenced by growth stage and farm type whereas variation in leaf K concentration was much more related to fertilizer application rates x growth stages interaction. Millet grain yield was influenced by fertilizer application rates but depended heavily on farm type. Significant positive relationships were obtained between pearl millet yield and stability of aggregate and plant available water thereby showing the importance of soil physical properties in explaining the variability in millet yield. APSIM model simulated grain and biomass yields with relatively good precision using both measured and generated climatic data, even though biomass yield was underestimated under the control treatment in both years. A socio-economic survey conducted confirmed the subsistence nature of the production system in Karabedji to be mainly characterized by low input-output and highly variable soil properties. Moreover, low purchasing power was viewed by most farmers as the main reason for inadequate use of mineral fertilizers. Some opportunities to overcome these constraints were revealed, including membership to farmers' associations, project interventions, presence of input shops and warrantage warehouses, which improved access to farm inputs and resilience capacity for non-resource endowed farmers. Average quantity of mineral fertilizer used varied from 3 to 14 kg ha^{-1} among farmers. The results could serve as policy guide for promoting more resource-efficient technologies for small-scale farmers use and required focus towards farmers' needs.

DEDICATION

This work is dedicated to my parents Garba Harouna Nomao and Zouéra Maniya; to my wife Bintou Mamadou Kouri Ibrahim; to our children Mahamadou and Nana Khadidja; and to my late brother Mahaman Maawiya Garba who I regretfully lost while completing this work.

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TABLE OF CONTENTS

Contents **Page**

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

1.0 INTRODUCTION

Soil fertility decline is a major concern in sub-Saharan Africa (Bationo and Waswa, 2011), particularly in Niger where 80% of the population live in rural areas (INS-Niger, 2012) and depend entirely on agricultural production for food and livelihood. In Niger, agricultural activities generally depend on a highly variable unimodal rainfall pattern spread over a 3 to 4 month period, i.e. June to September (Sivakumar and Hatfield, 1990; Sivakumar, 1992; Sivakumar *et al*., 1993; Greaf and Haigis, 2001; Van Vyve, 2006). Total annual rainfall in the pearl millet (*Penisetum glaucum* (L.) R. BR) production area ranges from 350 to 600 mm, with frequent dry spells.

Pearl millet is generally produced on highly weathered sandy soils in Niger which are inherently low in fertility. The poor fertility status of these soils combined with high variability in rainfall and high temperatures, characteristic of the Sahel region, exacerbate the situation by leading to more serious and frequent droughts responsible for crop failure.

Traditionally, farmers use local strategies for replenishing soil fertility such as long bush fallow, corralling, application of household and farmyard manure, and recycling of crop residues (De Ridder *et al*., 2004). However, due to high demographic pressure, these long duration bush fallow practices have been abandoned (Sanchez *et al*., 1997; De Rouw and Rajot, 2004; Samaké *et al*., 2005) and replaced by unsustainable soil management practices such as exposure of soil surface, crop residue removal, and use of marginal lands for cultivation. Unsustainable soil management practices favour degradation of soil physical, chemical and biological quality, indicated by complete loss of soil structure, sealing, crusting, compaction and excessive runoff on crust-prone soils; nutrient imbalance resulting from leaching losses; and decline in soil organic matter and reduced macro and micro fauna (Lal, 1983; Conacher, 2004). There is therefore the need to conduct investigation into appropriate soil management practices that can conserve soil and sustain crop production while replenishing and maintaining soil fertility.

Over the years, scientists in the region have evaluated the potential of several technologies in addressing the soil fertility problems of sandy soils with the aim of increasing food production (Bationo *et al*., 2007). The results of these investigations have shown that yields can be increased significantly on these soils with improvement of soil fertility using inorganic and organic amendments combined with soil and water conservation measures (Bationo *et al*., 2007; Sanginga and Woomer, 2009). However, there is poor adoption of soil fertility management practices, particularly with regard to the use of mineral fertilizers (Njeunga and Bantilan, 2005). Moreover, the use of organic residues which could serve as an alternative, is associated with several socio-economic constraints (Williams, 1999; Schlecht and Buerkert, 2004; De Rouw and Rajot, 2004; Abdoulaye and Sanders, 2005). A better understanding of the relationship between farmer socio-economic conditions and soil fertility management could help in addressing these adoption constraints.

Results from long-term experiments have so far helped to understand the long-term impacts of different soil management practices on crop yields and soil chemical properties - especially organic carbon (OC) which decreases with years of cultivation across all management practices in the Sahel (Subbarao *et al.*, 2000; Bationo *et al*., 2011). The effect of long-term soil management practices, particularly from on-farm trials, on the physical properties of Sahelian sandy soils and their impact on water and nutrient availability is however not known a priori. Soil fertility management practices by farmers of different socio-economic conditions are likely to have differential effects on soil fertility status and crop yield in the long-term. In-depth soil fertility assessment of specific responses of soil physical and hydrological properties to long-term management practices will provide insight into their long-term impacts on crop yield and fertility status of these highly weathered sandy soils. This could lead to the identification of several soil physical quality indices sensitive to management practices, as has been reported elsewhere in the world (Dexter 2004, Reynold, 2007; 2009), which could bring about the improvement of water availability to crops.

With regard to nutrient deficiency, it has been established that Sahelian sandy soils respond to nitrogen application after correction of phosphorus deficiency (Fofana *et al.*, 2008). The availability of phosphorus and nitrogen has to be considerably increased, in combination with improved organic matter content and soil physical properties, for sustainable food production in the Sudano-Sahelian zone of Africa (Ganry, 2001; Bationo and Buerkert, 2001). Understanding the inter-related physico-chemical and hydrological processes affecting pearl millet growth in the Sahel could help in explaining the frequently observed fluctuation in crop yields and in better prediction of millet yields through modelling. This could contribute to the knowledge of soil fertility implications of each management practice over the long-term and will help identify the most sustainable management practices suitable to local conditions.

It was therefore hypothesized that on the highly weathered Sahelian Arenosol, soil fertility degradation processes are driven by changes in soil physical quality, such as specific volume, air capacity, relative field capacity, porosity, structural stability, hydraulic conductivity; and organic carbon content all of which affect water and nutrient availability, and ultimately crop yields. It was also speculated that changes in physical properties and source of P can influence P uptake and crop yield and that short-term infiltration can predict macro-porosity of the soil. The magnitude of P uptake depends on the initial soil fertility level of the farm (farm type), and that soil physical quality indicators obtained from long-term experiments can be used to predict millet yields using Agricultural Production Systems Simulation Model (APSIM) model.

The main objective of this study was therefore to identify and recommend appropriate soil management practices for sustained yield of pearl millet on smallholder farms in the Sahelian zone of Niger. The specific objectives were to:

i. assess the effect of long-term inorganic fertilizer application on selected soil physical properties and their impact on the availability of P and concentration of P and K in millet leaf;
ii. determine the effects of soil fertility management levels on soil physical and hydrological properties;
iii. identify and evaluate key indicators of soil physical quality and their effect on crop yields;
iv. use the selected soil quality indicators to predict millet yields under farmer conditions using the APSIM model;
v. establish the relationships between farmers' socio-economic conditions of farmers and soil fertility management status.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Constraints to pearl millet production in the Sahelo-Soudanian zone of Niger

In Niger, pearl millet production areas are dominated by highly weathered sandy soils (Arenosols / WRB / FAO, 2006) that are inherently low in fertility. These soils are characterised by low water and nutrient holding capacities and high hydraulic conductivity favourable for nutrient leaching out of the root zone, resulting from their coarse texture, low clay and organic matter contents (Kang, 1985; Payne *et al*., 1991; Zaongo *et al*., 1994; Kyuma *et al*., 2001; Bationo *et al*., 2007). Payne *et al.* (1991) reported clay and sand content of about 5% and 92%, respectively, which only changed slightly with depth. The low water holding capacity of these soils combined with the rapid drainage and high evaporation is conducive to agricultural droughts. Moreover, the Sahelian sandy soil is characterized by high variability in soil properties (Scott-Wendt, 1988a; 1988b; Voortman and Brouwer, 2003; Voortman *et al*., 2004). In their study on the causes of variability in soil properties in pearl millet fields in semi-arid West Africa, Scott-Wendt *et al*. (1988a) reported that millet growth correlated with shoot K and Al concentrations and that poor growth was associated with deficient concentrations of P and K and potential toxic level of Mn. Understanding the causes of the high local variability in the properties of the Sahelian sandy soils, is key to proper interpretation of agronomic research and dissemination of research results (Voortman and Brouwer, 2003; Voortman *et al*., 2004).

Physical and hydrological properties of sandy soils of Niger cropped to millet have been studied by many researchers (Klaij and Vachaud, 1992; Payne *et al.*, 1991; Payne, 1997; Rockstrom *et al*., 1998; Manyame, 2006). Reports have shown that water can be used more efficiently for pearl millet production by decreasing drainage out of the root zone and by increasing the partitioning of rainfall to transpiration through improved management (Payne, 1999). Yet, there has been little on-farm studies on the impacts of such management practices on soil water balance. (Lal, 1992; Manyame, 2007).

Furthermore, nutrient deficiencies especially in P and N have been reported among the major constraints to crop growth on degraded sandy soils (Kang, 1985; Scott Wendt *et al*., 1988; Pieri, 1989; Kyuma *et al*., 2001; Michel and Bielders, 2006; Bationo *et al*., 2007). According to Fofana *et al.* (2008) millet responded to N application only if P deficiency is corrected, thereby making P the most deficient nutrient and one of the most limiting factors of millet production (Bationo *et al*., 2007). Fofana *et al*. (2008) compared fertilizer use efficiency between two farm types (Table 2.1) i.e. farms that were close to homestead (or infields) and farms that were far away from homestead (or outfields) at Karabédji, Niger. These authors reported higher pearl millet dry matter yield responses to P and N fertilization on infields compared to outfields. They emphasized the crucial role of P fertilization (especially for outfields) for millet production. Phosphorus and nitrogen availability has to be increased considerably together with an improvement of the soil organic carbon content and soil physical properties in order to attain a sustainable food production in the Sahelo-soudanian zone of West Africa (Bationo *et al.*, 1990; Bationo and Buerkert, 2001). Similarly, Buerkert *et al*. (2001) reported P placement as the most promising strategy to overcome P deficiency in West Africa. According to Michel and Bielders (2005), pearl millet yield tripled after addition of phosphorus, and increased by a factor of 13.5 when additional nitrogen was applied on eroded sandy soil in the Sahel.

To maintain the fertility of their fields, small scale farmers, traditionally, use soil fertility maintenance strategies, such as land fallow, crop rotation systems, recycling of residues and addition of manure (Sanchez *et al*., 1997). However, these practices have been abandoned and are being replaced by unsustainable farm management practices of repeated cropping without replenishing essential elements, such as nitrogen, phosphorus, potassium and calcium and the removal of crop residues (Heano and Baanante, 2006). Moreover, agricultural activities have been extended to marginal lands due to high demographic pressure. Such practices result in soil fertility depletion and degradation of soil physical quality i.e. loss of structure and excessive drainage, on deep sandy soils, sealing, crusting and excessive runoff on crust-prone sandy soils as reported by Rockstrom *et al*. (1998). Degradation of soil physical properties prevents the soil from fulfilling its different functions with respect to crop production - providing an optimal medium for plant growth, regulating and partitioning water, gas and energy flow and serving as a buffer or filter system (Topp *et al*., 1997).

Most farmers in Niger are resource-poor and thus are restricted to subsistence agriculture (Pender *et al*., 2008), a system in which, more nutrients are exported in harvested produce than are put back to the already fragile soils (Nutrient mining). Soil nutrient mining leads to complete loss of soil productivity particularly in Africa and is a major threat to food security (FAO, 1990; Stoorvogel and Smaling, 1990; Heano and Baanante, 1999; Sanchez, 2002; Bationo *et al*., 2007). In Niger, nutrient mining has been estimated to average 15 kg ha^{-1} of N, 2 kg ha^{-1} of P, and 11 kg ha^{-1} of K per year, equivalent to an annual loss of about 440 kg of millet grain and 1,860 kg of straw per hectare (Buerkert and Hiernaux, 1998; Smaling *et al*., 1997; Bationo *et al*., 2007; Pender and Kato, 2008).

Table 2.1. Soil characteristics of farmer fields (0-20 cm) at Karabédji, Niger (1999)

Parameters*	Bush fields	Compound fields	s.e.
pH H_2O	4.80	5.10	0.21
P-Bray^{-1} (mg kg^{-1})	4.40	6.20	0.47
Organic C (g kg^{-1})	1.50	1.60	0.04
Total N (mg kg^{-1})	118	135	6.36
Exch. K^+ (mmol kg^{-1})	2.06	3.48	0.55
Exch. Ca^{2+} (mmol kg^{-1})	2.41	3.67	0.56
Exch. Mg^{2+} (mmol kg^{-1})	1.35	1.95	0.34

*Values represent average for 9 farms per field type. Source: IFDC (2002), Fofana *et al.* (2008)

2.2 Farmers' socio-economic conditions and replenishment of soil fertility status

There is poor adoption of soil fertility management technologies by the resource poor farmers in the Sahel (Njeunga and Batilan, 2005; Schlecht *et al*., 2006) and a variety of constraints have been unveiled in several adoption studies. Ndjeunga and Batilan (2005) found that the limited productivity gain prevented the uptake of new technologies in West Africa, while De Rouw (2004) attributed non-adoption to differences in priorities between the researcher, whose aim is to improve yields, and the Sahelian farmers who seek to reduce risk of crop failure. Furthermore, a wide range of socio-economic constraints were indicated as reasons to the little to no external inputs use by farmers, such as mineral fertilizer or improved varieties (Heano and Baanante, 2006; Williams, 1999; Bationo and Buerkert, 2001; Ouédraogo *et al*., 2001; Bayu *et al*., 2004). Low mineral fertilizer use or application below recommended rates in Niger has been ascribed to poor farm income, poor access to credit, lack of purchasing power and poor knowledge (Abdoulaye and Sanders, 2005; Kelly, 2005; Ndjeunga and Batilan, 2005), whereas the use of organic residues depends highly on labour requirement and availability, farm size, farm ownership status and farm distance from villages (Williams *et al*., 1999). In case of crop residue management, adoption is additionally hindered due to its competitive domestic use for feed, building material and fuel. Furthermore, crop residues are required in large quantity while the practice of continuous cropping does not generate enough to be used appropriately (Williams, 1999; Ouédraogo *et al.*, 2001; Bayu *et al.*, 2004; Ouédraogo *et al.*, 2004; Schlecht and Buerkert, 2004). The adoption of soil conservation and water harvesting techniques is yet another option which is limited by manure shortage and lack of specific knowledge of erosion processes by farmers (Wildemeersch *et al.*, 2013).

Similar reports from eastern part of Africa indicated factors such as farmer's access to land and capital resources (Shepherd and Soule, 1998; Masvaya *et al.*, 2011) to be important determinants of decision to adopt Integrated Soil Fertility Management (ISFM) technologies or not. Mugwe *et al.* (2009) noticed farmers' ability to hire labour, age of household head, and household food security as important elements in the Meru South District of Kenya. However, Tittonell *et al.* (2005a and 2005b) studied diversity of soil fertility management among smallholder farms at both regional and farm level in western Kenya and identified different management strategies adopted by various household types to be directly linked with soil fertility status. The authors therefore stressed the need for an approach that combines analysis of farm management and soil fertility status for better comprehending opportunities for sustainable crop production.

2.3 Impact of soil fertility management practices on crop production and soil fertility

Over the years, a number of nutrients management practices for improving soil fertility and crop yields have been promoted in Niger and elsewhere in Africa (Bationo *et al.*, 2011). Among these technologies are: organic residues; conservation tillage; and cereal/legume rotation and planting techniques (Bationo and Mokounye, 1991; Bationo and Ntare, 2000; Adamou *et al*., 2011; Bado *et al*., 2004; Bationo *et al*., 2011; Kihara *et al*., 2011), soil erosion control and water conservation (Bielders *et al*., 2002; Fatondji *et al*., 2006) and the judicious use of mineral fertilizer i.e. fertilizer micro-dosing technique (Tabo *et al*., 2006; Tabo *et al*., 2011).

Micro-dosing technology was developed in an attempt to increase the affordability of mineral fertilizers while promoting early provision of adequate nutrients for optimal plant growth. The micro-dosing technology consists of applying relatively small quantities of fertilizer (2-6 g hill^{-1}) at sowing time, thus decreasing substantially the recommended amount of fertilizer that subsistence farmers needed to apply per hectare [i.e., from 170 to 20 kg ha^{-1} in the case of di-ammonium phosphate (DAP)]. The implementation of this technology has resulted in enhanced nutrient use efficiency (Buerkert *et al*., 2001; Bationo and Kumar, 2002; Tabo *et al*., 2005). Strategically targeted fertilizer use together with organic nutrient resources to increase fertilizer use efficiency and crop productivity at farm scale are basic principles of ISFM (Vanlauwe and Giller, 2006). Its integration with water harvesting techniques such as Zai and or Half-moon and organic manure has been reported to increase millet yields and influence water balance (Fatondji *et al*., 2011).

Short-term effect of micro-dosing technology on soil water balance and millet growth has been studied by Manyame (2006) at Fakara, Niger, during the year 2003 and 2004 growing seasons. This author evaluated fertilizer micro-dosing together with five manure practices and three millet cultivars. The results indicated that the technology was effective in raising pearl millet yield only under low fertility conditions but did not have a significant effect on water balance of sandy soils under pearl millet cultivation in the Fakara region. According to Manyame (2006), manuring, particularly corralling however, had the greatest effect on the yield and water use of pearl millet at all sites. Corralling reduced root zone drainage and increased evapotranspiration on pearl millet fields without posing the risk of water constraint during the growing season. However, the long-term effects of this technology on soil hydrological properties and nutrient status have not been studied. Sound soil management practices, alternatives to long fallow that could sustain crop production, while replenishing and maintaining soil fertility, are therefore necessary. Suzuki *et al*. (2014) evaluated the effect of traditional management practices on nutrient status of Sahelian sandy soil and reported higher total N in the fields close to homesteads where Farm Yard Manure (FYM) has been applied compared to fields that have not received any organic matter for decades. Their finding also reported corralling as one of the most economical practice for replenishing soil fertility on sandy soils.

2.4 Long-term impacts of management practices on soil physico-chemical properties and crop yield

Long-term experiments are essential for knowing the most suitable management practices which can maintain crop yield and soil fertility (Bationo *et al.*, 2011). Both on-station and on-farm long-term experiments have been conducted in Niger and elsewhere in Africa. In Niger, these experiments were started since 1982 at Sadoré, Gaya, Karabédji and Banizoumbou. Millet was grown under different rates and combinations of inorganic fertilizer, manure, crop residue, tillage practices, and cropping systems in order to identify sustainability indicators and optimize the use of organic and inorganic resources available to farmers.

Management practices that influence chemical properties have been reported. According to Subbarao *et al.* (2000), P fertilization, ridging with animal traction, and planting on ridges and rotation with cowpea increased the productivity of millet sustainably in 10 out of 11 years from an on-station long-term trial at Sadoré, Niamey. However, yields of millet declined significantly when intercropped with cowpea whilst organic matter declined linearly with years of cultivation. From an on-farm long-term experiment on farmers' evaluation of soil fertility restoration technology, Adamou *et al*. (2011) reported consistently significant increase in pearl millet yield following strategic placement of 4 kg P per hectare as NPK 15-15-15 and DAP (Di-ammonium phosphate) at planting. . The combination of water soluble P fertilizer with Tahoua Rock Phosphate (TRP) gave additional 200 kg grain yield of pearl millet per ha (Adamou *et al.*, 2011). However, Faso, Bado *et al.* (2004) observed increase in soil acidification and decline in maize yields after 5 years of continuous application of inorganic nitrogen fertilizer at Farakoba in Burkina. The acidity was corrected with the application of manure, phosphate rock and dolomite.

In their 17 years of Integrated Soil Fertility Management (ISFM) experiment in South-Western Nigeria, Vanlauwe *et al.* (2005) emphasized that measures that enhance nitrogen use efficiency were more crucial in determining the yield more than just increasing its input. Also, significant negative interactions were found between dolomite and potassium fertilizers. At Kabete, Kenya, Kamaa *et al.* (2011) reported that ISFM practices brought about diversity of soil bacterial and fungal communities. Their study helped to understand the important functional and structural soil microbial properties as influenced by soil fertility management. Legume-millet rotation with application of 30 kg ha^{-1} N appeared to be a viable option for millet production (Bationo and Ntare, 2000). The authors observed however, that fallow-millet rotation supplied more mineral N than legume-millet rotations.

According to Bationo *et al*. (2011), results of long-term experiment on soil fertility management in sub-Saharan Africa, generally showed decline in organic carbon cutting across the soil fertility management practices with years of cultivation. Also, crop yields and soil fertility decline have been reported in prolonged application of inorganic inputs alone. Application of mineral fertilizers alone on impoverished soils leads to positive crop yield responses but results from long-term experiments indicate that yields declined following continuous application of only mineral fertilizer (Bado *et al*., 2004; Bationo *et al*. 2011). Such declines might have resulted from (i) soil acidification by the fertilizers, (ii) mining of nutrients as higher grain and straw yields remove more nutrients than were added, (iii) increased loss of nutrients through leaching as a result of the downward flux of nitrate when fertilizer N is added, (iv) decline in soil organic matter-(SOM) with years of cultivation. Best results were obtained in treatments that combined inorganic and organic inputs (Bationo *et al.*, 2011).

Increase in organic matter can significantly improve soil physical quality thereby, increasing nutrient availability and water holding capacities (Bationo *et al.*, 2007). The practices that deplete the organic matter content of the soil (such as continuous cropping without addition of OM) and tillage are examples of management practices that negatively influence soil structure (Kay and Munkholm, 2004). On the other hand, soil microbial biomass is an important reservoir of available nutrients (nitrogen, phosphorus and sulphur) and regulates the cycling of organic matter and nutrients (Syers, 1997; Baaru *et al.*, 2007). According to Bationo *et al*. (2011), most studies intending to improve crop yield focus on the above ground (yield) production without investigating the changes in soil properties and the long-term implications for sustainability of such system.

Dunjana *et al.* (2012) reported that 7 years addition cattle manure and inorganic N-fertilizer did not significantly increase bulk density, macro aggregate stability and aggregate protected carbon on sandy soils of the Meruwa smallholder farming area of Zimbabwe. However, these parameters were conversely improved on clayey soils. Lal (1997) reported no effect of long-term tillage treatments on bulk density on a tropical Alfisol of Western Nigeria. The impacts of long-term management practices on soil physical properties on the Sahelian sandy soils has received little attention. Long-term changes in soil physical quality and its associated impacts on phosphorus and water availability, as affected by management, is not known a priori.

2.5 Assessment of soil physical and hydrological properties as influenced by management practices

2.5.1 Soil physical properties

Reynold *et al*. (2007; 2009) reported that organic carbon contents, dry bulk density, air capacity, relative water capacity and saturated hydraulic conductivity can be used as useful indicators of soil physical quality because they were sensitive to land management on a clay loam soil. Soil clay and silt contents play an important role in the stabilization of soil organic matter (Bationo and Buerkert, 2001). However, Moura *et al*. (2009) reported number of days with water stress and rootable soil volume as the most suitable indicators for assessing the quality of a sandy clay soil in Brazil as affected by the application of low and high quality plant residues.

Addition of organic manure and crop residue mulch have been reported to improve soil structural stability through their influence on soil organic matter (Blanco-Canqui and Lal, 2009). Crop residues mulch protects soil surface against insolation and erosive impacts of raindrops and blowing winds (Blanco-Canqui and Lal, 2009). Soil aggregates serve as barriers between microbes and enzymes and their substrates thereby controlling microbial turnover (Six *et al*., 2002).

According to Dexter (2004), the slope of the soil water retention curve (S) at its inflexion point is indicative of the extent to which the soil porosity is concentrated into narrow range of pore size. In most soils, larger values of S are consistent with the presence of a well-defined microstructure. Therefore, it is suggested that S can be used as an index of soil physical quality that enables to compare directly different soils and effects of different managements, treatments and conditions. Moreover, Dexter (2007) reported that S is a useful numerical value that can be used in equations to predict a range of soil physical properties. The author indicated how S can be used to identify areas where land physical degradation or amelioration is taking place, and to evaluate management practices that will be sustainable. However, Garba *et al*. (2011) reported no clear trend in soil physical quality index of Sahelian sandy soil amended with increasing rates of termite mound material in combination with organic manure and therefore suggested the search for more appropriate critical S values for this soil.

2.5.2 Soil hydraulic properties

Diagnosis of surface hydraulic properties is necessary for adequate soil fertility management, as these properties influence the partitioning of rainfall and soil water storage (Bodhinayake and Si, 2004). These include total porosity, hydraulic conductivity and soil water content as a function of matric potentials.

2.5.2.1 Soil macro-porosity

The proportion of different size ranges of macro pores contributing to total soil water flow by adjusting the hydraulic potential of the water supply can be estimated using tension disc infiltrometers. It is used for non-destructive soil structure measurement and for quantification of macro-porosity (Perroux and White, 1988). Number and fractions of hydraulically effective macro pores have been derived in agricultural and forest soils using tension disc (Buczko *et al*., 2006). Buczko *et al*., 2006 characterized macro-porosity and surface saturated hydraulic conductivity of silt loam and sandy loam soils under conventional and conservation tillage systems using ring and tension disc infiltrometers. Values of saturated hydraulic conductivity (Ks) found were by one order of magnitude higher than the values estimated using soil texture which implies that soil structure has a dominant influence on hydraulic conductivity. According to the authors, conservation tillage showed higher macro-porosity than conventional tillage. They also observed higher Ks value with the ponded ring infiltrometer than with the tension disc at the sandy site. The difference was ascribed to subcritical water repellency although other factors could also be important (e.g. air entrapment, differences in water saturation, geometry of infiltration devices).

Other methods to characterize macro-porosity include dye tracer experiments (Droogers *et al*., 1998), inventory of macro pores in the field (Logsdon *et al*., 1990), image analysis (Carof *et al*., 2007), resin impregnation techniques (Singh *et al*., 1991), X ray tomography (Anderson *et al*., 1990), calculation from laboratory measured water retention characteristics (Carter, 1988; Reynold, 2007) or from soil water content directly beneath tension infiltrometer measurement sites (Bodhinayake and Si, 2004).

2.5.2.2 Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) is a key parameter of water and solute transport models as it influences their storage and movement (Gwenzi *et al*. 2011). K_{sat} can be estimated from infiltration measurement on the field using tension disc infiltrometer which is a valuable and popular device for in situ measurement of hydraulic properties (at water pressure heads close to saturation (Ankeny *et al*., 1991; White *et al.* 1992; Logsdon and Jaynes, 1993). Ouattara *et al*. (2007) assessed the effect of different tillage practices on soil infiltration parameters, using tension infiltrometer on loamy and sandy loam soil types of the western cotton zones in Burkina Faso. They reported reasonable agreement of soil hydraulic behaviour with pore size distribution by tillage frequency and organo-mineral fertilization. Manyame *et al*. (2007) however evaluated hydraulic properties of sandy soils at Banizoumbou and Bagoua in Niger, using Campbell and van Genuchten functions. The authors concluded that the Campbell model can be used as a cheap alternative to direct measurement of soil moisture retention whereas the van Genuchten model can be used to estimate hydraulic conductivity with modest accuracy.

Different methods are used to analyse data from measurement with tension disc infiltrometer. Two main groups can be distinguished: the steady-state methods (Ankeny *et al*., 1991; White *et al*., 1992; Logsdon and Jaynes, 1993) and the transient methods (Turner and Parlange, 1974; Smettem *et al*., 1994; Zhang, 1997). Zohrabi *et al*. (2012) estimated unsaturated hydraulic conductivity and soil moisture retention curve from tension disc infiltrometer data in sandy soil with a good approximation using the method proposed by Logsdon and Jaynes (1993).

However, on crusted soils the magnitude of saturated hydraulic conductivity may differ between the surface crust and the underlying soil. According to Vandervaer *et* *al.* (1997), who validated the transient flow method to estimate hydraulic conductivity of crusted soil in Niger using tension disc and mini tensiometers simultaneously, the ratio of the saturated hydraulic conductivity of the crust to that of the underlying soil ranges from 1/3 to 1/6 depending on whether the crust is of a structural or sedimentary type. But, on non-crusted soil, particularly on millet fields these authors reported that persistent effects of localized working of soil during weeding operations caused large variations in infiltration fluxes between the sampling points. Consequently, they cautioned as to the use of transient flow method in case of high heterogeneity unless a very large number of tests is performed.

Higher effects of spatial variability than the supplied potentials were also reported (Vanderveare *et al*., 1997). These effects interfered with correct estimate of hydraulic conductivity using tension disc on millet fields. Possible reasons for poor estimate of hydraulic conductivity may be restriction to flow from tubes or air in the mariotte system which supplies water or from the membrane (Reynold, 2000; Buczko *et al.*, 2006).

Soil hydraulic conductivity is the soil ability to receive and transmit water when subjected to hydraulic gradient. This parameter influences runoff versus water entry into the soil during precipitations and could be a good indicator of low yield caused by poor soil physical properties. Keller *et al.* (2012) reported lower field saturated hydraulic conductivity in the subsoil of low yielding field zones compared to average and high yield parts. The authors concluded that the low saturated hydraulic conductivity was as a result of high bulk density and average mean weight diameter of aggregate and blocky structure. Bruand *et al*. (2005) reported that soil saturated hydraulic conductivity varies according to development of macro-porosity. However, when cultivated the macro-porosity of sandy soil collapses rapidly in the presence of water.

There is a great advantage of using tension infiltrometer over the single and double rings methods, which are commonly used, in the determination of soil hydraulic conductivity. This advantage is that the effect of pore size distribution on infiltration can be determined by varying the negative water pressure thereby eliminating pores of certain size from the flow process.

2.5.2.3 Soil water retention characteristics

The soil water retention curve (SWRC) expresses the relation between the soil water pressure head h (cm) and the volumetric soil water content θ_V (m^3 m^{-3}). At pressure head h = 0 cm, the soil is saturated and the moisture content is in theory equal to porosity ($\theta_V = \theta_S$). However, when the soil wets quickly, air entrapment occurs in the pores and the soil water content is less than porosity. When h decreases, the soil water content does not decrease immediately as well. But as soon as h is smaller than air entry value h_A, air can enter the soil and the soil water content can decrease (Cornelis *et al*. 2005). The decrease in water content can go rapidly or slowly depending on soil type, the decrease and the magnitude of the hydraulic pressure. At a certain hydraulic pressure, the hydraulic conductivity becomes very small and the corresponding water content is called residual water content θ_r. Different forces act on soil water and are responsible for its retention in the soil matrix. Capillary forces are dominant between 0 and -10^{-2} kPa pressure head, whilst osmotic forces become determinant between -10^{-2} kPa and -10^{-4} kPa. Adsorption forces are the principal forces between -10^{-4} kPa and -10^{-6} kPa (Hillel, 1998). Soil water content can be defined as volumetric water content θ_V (m^3 m^{-3}) which is the volume of water per bulk volume of soil or as mass content θ_g (kg kg^{-1}) which is expressed relative to the mass of oven dry soil (Warrick, 2002).

2.6 Soil chemical properties as influenced by management practices

Soil chemical properties of sandy soil sensitive to management practices have been reported. According to Yamoah *et al*. (2002), the combination of crop residue and mineral fertilizer gave greater yields and return than either crop residue or mineral fertilizer alone in nine cropping seasons. Previous report (Geiger *et al*., 1992) showed that the combinations favoured higher availability of P and exchangeable bases and lower Al-saturation compared to the control at Sadoré, Niger. Hafner *et al*. (1993) reported beneficial effects of crop residues on P uptake by millet and attributed it to decreased concentrations of exchangeable Al and enhanced root growth whereas, beneficial effects of exchangeable K uptake was attributed to direct K supply with millet straw.

Higher particulate organic matter content on rich farmers' fields compared to poor farmers' fields among maize growers was reported in Zimbabwe (Mtembanengwe and Mapfumo, 2008). Variability in soil organic carbon resulting from field-specific management is common among farming systems in Sub-Saharan Africa (Tittonell *et al*., 2005a; 2005b; Bationo *et al*., 2007; Dunjana *et al*., 2012). It has been established that organic matter decreases with depth (Bationo *et al.*, 2007).

Suzuki *et al*. (2014) evaluated the effect of traditional management practices on nutrient status of Sahelian sandy soil and reported higher total N in the fields close to homesteads where farm yard manure has been applied compared to field that did not receive any organic matter for decades. The general low N content observed in their study was attributed to low N inputs resulting from the small quantities applied as fertilizer and the poor quality of transported manure (Hayashi *et al.*, 2009; Suzuki *et al.*, 2014).

In their study on the causes of soil variability on pearl millet fields in semi-arid West Africa, Scott-Wendt *et al.* (1988a) reported that critical nutrient concentration in millet vary with growth stage and that millet growth correlated with shoot K and Al concentrations. They also indicated that poor growing plant had deficient concentrations of P and K and potential toxic level of Mn.

2.7 Modelling soil response to management practices in the tropics

In their analysis of relevant studies on soil fertility and soil fertility restoration in sub-Saharan West Africa (SSWA), Schlecht *et al.* (2006) reported that inconsistency and incomplete concomitant consideration of biophysical and socio-economic parameters that determine soil fertility and its management are among the main factors that jeopardize the success of technology transfer. They stipulated that the wealth of detailed data on biophysical and socio-economic aspects of soil fertility and its management in SSWA needs to be integrated into a data base to serve as input for models geared towards the assessment of sustainability of soil fertility management options.

According to Bationo and Buerkert (2001), GIS, modelling and simulation should be used to combine (i) available fertilizer response data from on-farm and on- station research, (ii) results from soil productivity restoration with the application of mineral and organic amendments and (iii) the current knowledge of the cause-effect relationships governing the prevailing soil degradation processes, in order to predict the effectiveness of soil fertility management in conserving and or improving soil organic carbon in the Sahel. Akponiké *et al.* (2014), in a review, presented and compared the potential and currently used soil water crop models for use as decision support system. The authors suggested that crop modelling in millet-based agricultural system of the Sahel should be addressed with an integrated approach that can handle the complex agro-ecosystem in the region.

Agricultural Production Simulation System (APSIM) and Decision support system for agro-technology transfer (DSSAT) have been used to simulate millet growth and development, predict long-term yields of millet and to assess the suitability of soil management techniques currently in use in the Sahel (Akponiké, 2008; Soler *et al*., 2008; Akponiké *et al*., 2010; Adamou *et al*., 2011; Jones *et al*. 2012, Rezaei *et al*., 2014). APSIM has some advantages over other crop models such as DSSAT as it focuses not only on simulating soil processes - effect of climatic and other management factors on soil processes (Zhu *et al*. 2011) but it also provides flexibility with its modularized design: single modules describing processes on climate, soil, water, plant nutrition, and crop physiology, are developed and used as building blocks for the whole model (Zhu *et al*. 2011). The main shortcoming of APSIM however, is its inability to simulate phosphorus balance, likewise for other biotic stress stresses such as pests, diseases and weeds are not simulated (Akponiké *et al*., 2014).

Several Sahelian pearl millet genotypes (both improved and landraces cultivars) have been parametized for use in crop growth models - e.g. APSIM and DSSAT (Akponiké, 2008; Soler *et al.,* 2008). APSIM successfully reproduced the response to water and N interaction of CIVT millet cultivar from combined application of crop residues, cattle manure and mineral fertilizer (Akponiké *et al*., 2010).

2.7.1 The APSIM model

APSIM is a crop simulation model that simulates crop development, growth, water and N dynamics and interactions among climate, soil fertility, crop and residue management practices (Keating *et al*., 2003). It uses daily weather data on rainfall, solar radiation, maximum and minimum temperature. It predicts crop potential yield in a given environment limited by water, temperature, solar radiation and N supply. APSIM is used in several applications such as support for on-farm decision making, faming system design for production and resources management oriented projects, waste management, risk assessment for policy making and as guide for research and education activities (Keating *et al*., 2003).

2.7.1.1 APSIM-millet module

The APSIM-millet module was originally parameterised based on an on-station data from ICRISAT-Patencheru, India (van Oosterom *et al.* 2001). This module was validated for the Sahelian soils, millet cultivars and climatic conditions by Akponiké (2008) under optimum growing conditions, covering a range of planting dates and genotypes. It simulates the growth and development of millet on daily basis. The module components include: phenology, biomass partitioning, roots, biomass retranslocation, leaf development, tillering, regrowth, water uptake, water deficit affecting plant growth, nitrogen uptake and retranslocation, N fixation, root growth and distribution, temperature stress and plant death. The APSIM-millet module is linked with other modules in APSIM system in order to simulate crop growth and development. Some of these modules are described as follow:

2.7.1.2 Fertilizer module

The fertilizer module allows the user to specify the application of solid fertilizer. Any module in APSIM can request fertilizer application using standard APSIM messages.

The data required to specify the operation is the amount of fertilizer to apply, the type, the depth and the date.

2.7.1.3 Soil Water Module

This module is a cascading water balance module and allows the user to specify water characteristics of the soil in terms of the lower limit (ll15), drained upper limit (dul) and saturated (sat) volumetric water contents. Saturated and unsaturated algorithms are used to describe water flow in this module. Redistribution of solutes such as nitrate and N-urea is carried out in this module. Connected to this module, is the residue and crop modules so that simulation of soil water balance responds to change in the status of surface residues and crop cover. Various processes are calculated daily and consecutively - the initial soil water, runoff, evaporation, saturated and unsaturated flow, solute movement, leaching, above flow saturation, run-on, lateral inflow and outflow capabilities on a layer basis.

2.7.1.4 Other modules

These are the SoilN, SoilP and Manure modules. The SoilN module describes the dynamics of C and N in the soil. The SoilP module handles P fertilizers that are readily available or slow release and the placement type. It represents the soil's ability to supply P to crops that can be used in crop module to modify growth processes under P limiting conditions. The Manure module handles the release of P from manure to the soil surface as function of time and moisture content.

2.7.1.5 Minimum data set

Minimum data set to run the APSIM model include weather condition, crop management, soil and crop response data, and soil input parameters such as depth, physical and chemical properties, slope, etc. Weather data include rainfall, solar radiation, minimum and maximum temperatures for the study site or a nearby meteorological station. However, stochastic weather generator models can also be used to complement or substitute historical weather data (Soltani and Hoogenboom, 2007; Qian *et al*., 2011). MarkSIMGCM, an online tool developed by Waen Associates UK in partnership with CGIAR Institutes can be used to generate long-term weather data (http://ccafs.cgiar.org/marksimgcm#.U_rdXPl5NSM). Crop management data include planting date, planting mode, planting depth, and spacing, date of emergence, crop tillage practices, fertilization and harvesting.

2.8 Summary of literature review

The literature reviewed shows the nature and extent of soil fertility related constraints affecting pearl millet production in Niger, particularly the low water and nutrient holding capacities and the deficiency of N and P. Organic matter and P availability together with improvement in soil physical properties are pre-requisites for sustainable food production in sub-Saharan Africa. Research efforts are being made towards adequate development of soil fertility management technologies. However, the adoption of these techniques remains poor due to socio-economic factors affecting resource poor farmers. A better understanding of these socio-economic factors could help in devising more appropriate techniques affordable to the farmer thereby addressing adoption constraints. However, there is limited knowledge about the relationship between farmer's socio-economic conditions and the use of soil fertility management practices on the farm as compared to other parts of Africa. Nutrient management techniques for improving soil fertility and crop yield have been reported and promoted by scientists at both local and regional levels. Among these techniques are the use of organic residues, conservation tillage, cereal/legume rotation, soil and water conservation measures and judicious use of fertilizers (fertilizer micro-dosing). Moreover, results from long-term experiments in Niger and elsewhere in Africa have helped in understanding the long-term impacts of soil fertility management techniques such as the general decline in organic matter cutting across soil fertility management practices over years of cultivation and the importance of integrating both inorganic and organic amendments sources. These research breakthroughs are more related to soil chemical properties than to physical properties. The long-term impacts of soil physical changes on soil physical quality and the associated impacts on soil and water availability have been poorly investigated. Elsewhere, several reports have shown the impact of changes of soil physical and hydrological properties on soil physical quality and the potential impacts on crop yield. Finally, the literature indicated that modelling soil response to management practices can help in better and simultaneous consideration of interconnected limiting factors while developing soil fertility management technologies in the Sahel. The APSIM model has been used in the Sahelian environment and, due to its several advantages, has been viewed as one of the most promising crop growth models for use in the Sahelian agro-ecosystem.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Study site location

This study was carried out at Karabédji (13°16’17”N, 2°30’33”E) which is situated at about 60 km from Niamey in the south-western part of Kouré District, Niger (Figure 3.1).

3.1.2 Climate

The climate is of the Sahelo-Soudanian zone characterized by 3-4 months growing season (from July to September) and 8 to 9 months of dry season (October to June). Rainfall in the area is highly variable in time and in space (Van Vyve, 2006). The average rainfall is about 600 mm per annum (Figure 3.2). Average minimum and maximum temperature range is between 16-42 °C, characteristic of the semi-arid regions (Greaf and Haigis, 2001).

3.1.3 Dominant soil type

The dominant soil at the study site is sand classified as Arenosol (FAO, 2006) or Psammentic Paleustalfs (Soil Survey Staff, 1975). This soil is characterized by coarse texture, high infiltration rate, low organic carbon content, and low nutrients and water holding capacities.

3.1.4 Agricultural production system

The dominant agricultural system is subsistence crop-livestock system typical in the Southern Sahel. Pearl millet is grown by farmers in sole, in mixed cropping with sorghum, groundnut, and cowpea and in rotation with legumes viz. cowpea, bambara nut and groundnut.

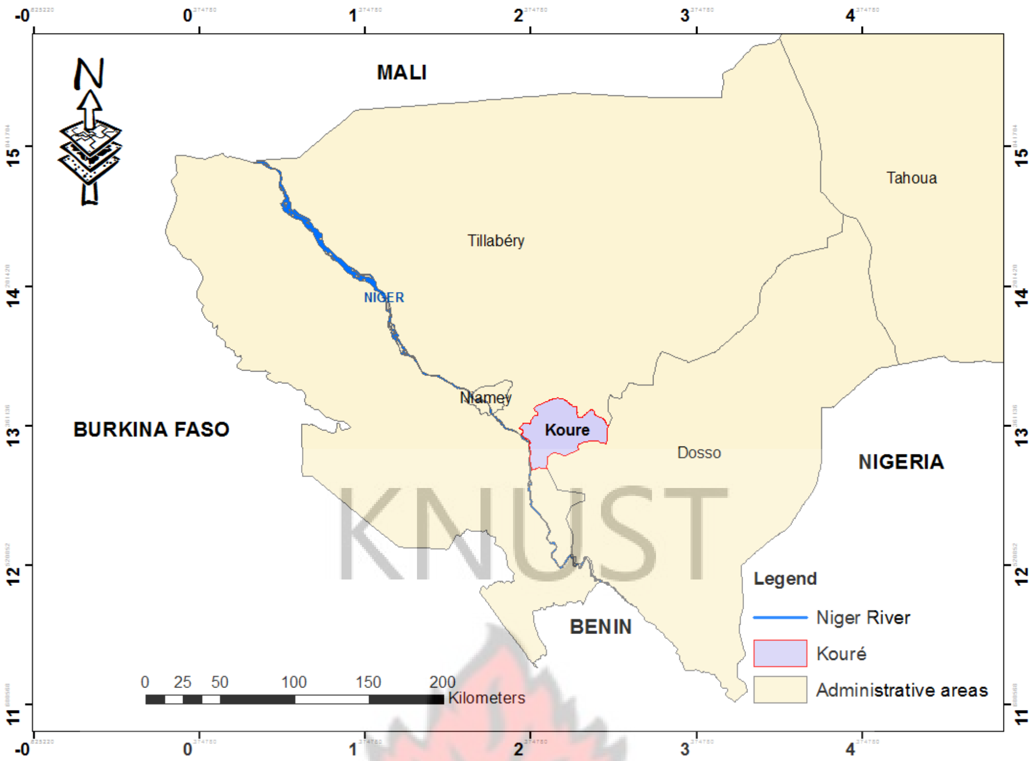

Figure 3.1. Location of experimental site in Kouré District, Tillabéri, Niger. Source: SIG-Niger Database terrain, 2013

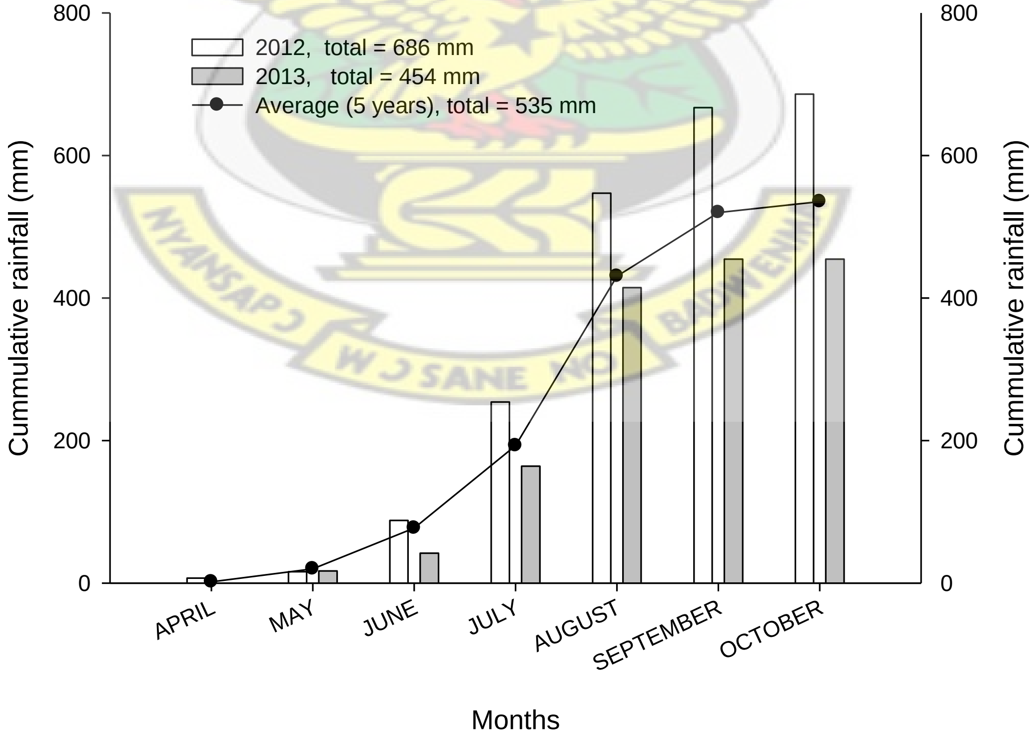

Figure 3.2. Rainfall distribution at Karabédji, Niger

3.2 Experimental setup / treatments

This study was conducted over two growing seasons (2012 and 2013) on 8 farmers' fields selected from 23 farmers who are involved in an on-going long-term evaluation of soil fertility restoration technologies. This evaluation of soil fertility restoration technologies was established in 1999 and consisted of millet grown under four treatments (inorganic fertilizer rates) laid out in a Randomized Complete Block Design (RCBD) with two blocks each on 23 farmers' fields. The aim of this long-term on-farm trial was to identify sustainability indicators and optimize the use of both organic and inorganic resources available to famers. The treatments were designed to test two sources of P used for fertilizer micro-dosing and the full rate of P from rock phosphate ("Tahoua" rock phosphate commonly found in Niger) that will mitigate the potential risk of soil mining of available P after continuous applications of micro-dose rate.

The experiment consisted of four inorganic fertilizer rates laid out in RCBD with four replications in each of the two farmer types (top and bottom farmers). The treatments consisted of: T_0 = control (farmer practice with no inorganic fertilizer applied), T_1 = 4 kg P ha^{-1} as DAP, T_2 = 4 kg P ha^{-1} as NPK 15-15-15 ha^{-1} and T_3 = 4 kg P ha^{-1} as NPK 15-15-15 + 13 kg P as "Tahoua" rock phosphate (TRP). TRP used contains 25% P_2O_5; DAP contains 18% N and 46% P_2O_5 and NPK contains 15% N, 15% P_2O_5 and 15% K_2O. Each plot measured 15 x 15 m with a 1 m alley allowed between the treatments. The treatments were based on the two fertilizer micro-dosing rates being disseminated to farmers i.e. 2 g of DAP and 6 g of NPK 15-15-15 per millet hill, and 13 kg rock phosphate added to the NPK 15-15-15 rate per ha to arrest possible effects of P mining.

3.3 Experimental field selection

In selecting the experimental fields, farmers were ranked based on an average of 13 years (long-term) millet grain yields. This criterion was complemented with the diagnosis of soil fertility status of each farm. One block was selected on each of the four top farmers' fields (those with highest yield records), and on each of the four bottom farmers' fields (those with lowest yield records). A socio- economic survey was conducted to establish the relationship between farmer's socio- economic conditions and soil fertility management practices. Crop residues and manures application are common management practices among farmers. Organic manures used by farmers in the study area consisted of farm yard manure, household manure, cattle and sheep and goat manure, and generally contained 33-36% total carbon, 0.56-2.26% total N, 0.057-0.20% available P and 0.27-0.87% for exchangeable K (Suzuki *et al.* 2014; AFNET, 2002). Locally used manure is of poor quality due to its high C:N ratio (varying from 15-30) resulting from its high crop residues C and low N contents (Suzuki *et al*., 2014).

3.4 Planting and crop management

Pearl millet variety "Haini kirey", commonly used by farmers in the region, was planted at a density of 10 000 hills per hectare (1 m x 1 m) in June, 2012 and in July, 2013. Fertilizer was applied just after rainfall at approximately 2 weeks after planting. All other agronomic practices such as thinning, weeding, fertilizer application and harvesting were carried out by farmers themselves under close supervision by a technician. Rainfall amount was measured using a rain gauge which was read immediately after each rain event.

3.5 Parameters assessed

Soil physical, hydrological and chemical properties, and total phosphorus, and potassium concentrations in millet leaf were measured on each of the selected fields over the two growing seasons.

3.6 Soil sampling

For the determination of soil chemical properties, five soil samples were taken at random from each plot by means of auger, at the beginning and at the end of the growing season. The five samples were then bulked and composite samples representative of each plot taken. The soil samples were taken at depths of 0-10 and 10-20 cm. Neighbouring fields under long-term (> 10 years) fallow were also sampled. Composite samples were put in plastic bags, labelled and taken to the laboratory where they were air-dried at room temperature and sieved using a 2 mm mesh for laboratory analyses.

For water-stable aggregate and structural stability determinations, natural clods were randomly collected, by means of shovel, from 0 to 20 cm depth at three spots from each plot. These clods were then composited and put in labelled plastic bags and carefully taken to the laboratory. To avoid clods breaking, rigid containers were used during transportation.

For soil water retention characteristic curve (SWRC) and water content at field capacity determination, undisturbed moist soil core samples were randomly taken from two (2) spots in each plot at 0-10 and 10-20 cm depths using labelled Kopecky core rings (with a ring depth of 0.05 m and a radius of 0.025 m). Care was taken to remove the upper 2.5 cm before inserting the core rings (in order to avoid collecting grasses, leaves, pebbles and other debris). After taking the sample, each ring was immediately covered with plastic sheet, then labelled and put in a sampling box.

3.7 Plant sampling

Millet leaves were sampled at three growth stages viz. tillering, flowering, and maturity in order to monitor phosphorus and potassium concentrations in the leaves. This was to facilitate the assessment of the impacts of changes in soil physical properties resulting from inorganic fertilizer application under different farm types on nutrient availability. Fully matured leaves were randomly collected from each treatment plot, labelled and taken to the laboratory in envelops where they were dried at room temperature. The leaf samples were oven dried at 70 °C for 10 minutes before grinding.

3.8 Laboratory analyses

3.8.1 Soil physical and hydrological properties

3.8.1.1 Particle size distribution

This was determined by the pipette method as described by INRAN (Institut National de la Recherche Agronomique du Niger) Soil Science Laboratory. The pipette method is based on sedimentation of particles by gravity according to the law of Stokes. Recovery of the aliquot at a given depth and a given time makes it possible to identify a specific class of particles when all the particles bigger than the selected diameter have been eliminated.

Pretreatment of soil sample was carried out to destroy and remove calcium carbonates, organic matter, iron oxides and soluble salts from the samples. Fifty grams of air-dried soil sample was transferred into a 200 mL beaker, add 50 mL of hydrogen peroxide added then covered with a watch glass and allowed to stand overnight. The following day, the beaker, covered with a watch glass, was placed on a hot plate until boiling for the destruction of organic matter (clear supernatant liquid and without bubbles). Further treatment with deionized water was done as necessary. Excess hydrogen peroxide was eliminated by boiling more vigorously for 1 hour. Five drops of ammonia were added and the suspension was boiled for another 30 minutes. The sample was transferred into a 1000 mL graduated sedimentation cylinder, rinsed the beaker using a wash bottle and 25 mL of pyrophosphate (or sodium hexametaphosphate) solution was added by means of a pipette and made up to volume with distilled water.

To determine the clay and silt (C + S) fraction, the content of each cylinder was mixed using a metallic rod by hand for 2 min. The eyedropper Robinson fraction C + S was taken at 10 cm deep after 3.32 min. (corresponding to the temperature 32 °C of the suspension and 10 cm depth). The sampled fractions were put in numbered boxes of known weights. The open boxes containing the pipetted suspensions were placed in an oven at 105-110 °C for 24 hours. The boxes were removed thereafter from the oven and immediately put in a desiccator to cool. Then the boxes with the fraction were weighed on an analytical balance of precision 0.1 mg (0.0001 g).

The clay (C) fraction was determined using the same steps as for fraction C + S, but with a time corresponding to the clay fraction which was 2 hours 57 min. The suspensions were put in boxes of known weights, dried in oven at 105-110 °C for 24 hours. The boxes with the dried clay fractions were weighed after cooling in a desiccator.

Calculations:

Clay (%) = $\frac{(TC_2 - TC_1) - B}{V \times P} \times 1000 \times 100$

Where, TC1 = weight of empty box (g),

TC2 = weight of box + dried clay (g),

B = correction factor due to the presence of sodium hexametaphosphate,

V = volume of pipetted fraction (mL),

P = weight of soil sample (g).

Clay + Silt (%) = $\frac{T(C+S)_2 - T(C+S)_1 - B}{V \times P} \times 1000 \times 100$ (1)

Where, $T(C+S)_1$ = weight of empty box,

$T(C+S)_2$ = weight of box + dried clay and silt,

Silt (%) = [Clay + Silt (%)] – Clay (%) (2)

3.8.1.2 Soil bulk density

Bulk density (ρ_b) was determined by the core method expressed in Mg m^{-3} as the ratio between the Mass *Ms* (expressed in Mg) of oven dry soil (at 105 °C for 24 hours) and the sample volume *Vt* (m^3):

$$\rho_b = \frac{Ms}{Vt} \quad (3)$$

Soil specific volume (*Sv*) is the inverse of bulk density:

$$Sv = \frac{1}{\rho_b} \quad (4)$$

3.8.1.3 Soil total porosity

Soil total porosity (*f*) was calculated using the relationship:

$$f = 1 - \frac{\rho_b}{\rho_s} \quad (5)$$

where ρ_s is the particle density of sand assumed as 2.65 ($Mg.m^{-3}$).

3.8.1.4 Soil water retention characteristics

This was determined in the laboratory using undisturbed core ring procedures as described by Cornelis *et al*. (2005). Saturated soil samples were subjected to different matric potentials (-1, -3, -5, -7, -10 kPa or pF 0-2) using the suction Table (Eijkelkamp Agrisearch Equipment, the Netherlands) and higher matric potential (-30, -100 and -1500 kPa or pF 3-4.2) using the pressure plate (Soil Moisture Equipment, Santa Barbara, CA, USA).

After weighing the soil samples at equilibrium for the matric potential -10 kPa, sub-samples were taken and the moisture content on mass basis was determined after oven drying at 105 °C for 24 hours. This enabled the calculation of bulk density (ρ_b) and gravimetric moisture content (θ_m) of the sample at each matric potential, as well as the volumetric water content (θ_v) using the relationships:

$$\theta_m = \frac{M_w}{M_s} \quad (6)$$

$$\theta_v = \theta_m \times \frac{\rho_b}{\rho_w} \quad (7)$$

where M_w = mass of moist soil sample, ρ_w = density of water

RETC for Windows software version 6.0 (van Genuchten *et al*., 1991) was used to fit the van Genuchten (1980) model to the observed data pairs:

$$\theta = \theta_{PWP} + (\theta_s - \theta_{PWP})\left[1 + (\alpha.h)^n\right]^{-m} \quad (8)$$

where θ is the actual volumetric water content,

θ_s is the saturated water content, it was set at a value of 95% of total porosity (rule of thumb),

θ_{pwp} is the residual water content as the water content at the wilting point (-1500 kPa), h is the water potential,

α is a curve fitting parameter (the inverse of which relates to the air entry value), and

m and n are dimensionless parameters related to the pore size distribution (van den Berg *et al*., 1997).

3.8.1.5 Soil air capacity, AC

AC (m^3 m^{-3}) of undisturbed field soil is defined as:

$$AC = \theta_s - \theta_{FC}\ ;\ 0 \leq AC \leq \theta_s \quad (9)$$

where θ_s (m^3 m^{-3}) is the saturated soil water content,

θ_{FC} (m^3 m^{-3}) is the field capacity (gravity drained water content) taken here as volumetric water content retained at -10 kPa.

3.8.1.6 Relative field capacity (RFC)

RFC (dimensionless) is the soil's ability to store water and air relative to the soil's total pore volume (represented by θ_s):

$$RFC = \frac{\theta_{FC}}{\theta_s} \qquad (10)$$

3.8.1.7 Plant available water capacity - *PAWC* (m^3 m^{-3})

This indicates the soil's ability to store and provide water that is available to plant roots:

$$PAWC(m^3 m^{-3}) = \theta_{FC} - \theta_{PWP} \qquad (11)$$

where θ_{PWP} (m^3 m^{-3}) is the water content at permanent wilting point;

$0 \leq PAWC \leq \theta_{FC}$,

3.8.1.8 Soil structural stability

The most common procedure for assessing water stability of aggregates is the wet sieving method (Yoder, 1936). However, the attempt was made to use the wet sieving method resulted in the disintegration of all aggregates due to the sandy nature of the soil. Soil structural stability was therefore assessed using the water drop method (Diallo *et al*., 2004) and the Dexter structural stability index:

3.8.1.8.1 The water drop method

A clod of about 4 g, placed on a small holder, was subjected to a flux of 0.1 mL volume drops of water falling from a burette placed 1 m above. The material from the disintegration of the clod was passed through a funnel and was collected below in a 250 mL beaker. A 2 mm sieve was placed on the beaker to collect macro aggregates which were later dried and weighed. The volume of water (in mL) necessary to completely disintegrate the clod was directly read on the burette (adapted from Diallo *et al*., 2004).

3.8.1.8.2 Dexter index of soil physical quality ("the S theory")

S value represents the magnitude of the slope of the water release curve at the inflexion point when the curve is expressed as gravimetric water content, θ_g (kg kg^{-1}), versus the natural logarithm of pore water tension head (Dexter, 2004). The resulting parameters (Appendix 1) of the van Genuchten (1980) equation for soil water retention were used to obtain the soil quality index (S) which was reported by Dexter (2004) to be related to the sharpness of pore size distribution and indicative of the presence of micro structure. S can also be used to predict soil friability and breakup during tillage. It is expressed as:

$$S = -n(w_s - w_r)\left[1 + \frac{1}{m}\right]^{-(1+m)} \qquad (12)$$

where S is soil physical quality index,

w_s and w_r are the saturated and residual gravimetric water contents, respectively,

m and n are dimensionless parameters related to pore size distribution,

$m = (1 - \frac{1}{n})$ is a van Genuchten parameter for soil water retention.

Note that Dexter (2004) set $w_r = 0$. This was also done in this study when determining the van Genuchten parameters by curve fitting using the gravimetric water content.

3.9 Field saturated hydraulic conductivity (K_{fs})

K_{fs} was assessed in the field by means of tension disc - Model 2800 soil moisture equipment corp. Santa Barbara, CA, USA (Figure 3.3). Infiltration was measured on two randomly selected spots in each treatment plot. The depth (cm) of infiltration of water was recorded per unit time (every minute) until the steady stage has been attained using the multi pressure (-12, -9, -3 and 0 cm) procedure as described by Logsdon and Jaynes (1993). Infiltration data were analysed using the steady state flow method:

Logsdon and Jaynes (1993) assumed Gardner's (1958) K (h) relationship (13) and estimated the K_{fs} and α_g parameters from all different h_0 and q data simultaneously by using non-linear regression. More than two measurements (h_0, q) were needed for a correct regression:

$$K(h) = K_{fs} \exp(\alpha_g h) \qquad \text{Gardner's equation} \qquad (13)$$

where K is the unsaturated hydraulic conductivity (LT^{-1}),

K_{fs} is the field saturated hydraulic conductivity (LT^{-1}), and

h is the water potential (L).

$$q(h_0) = \left(1 + \frac{4}{\pi r_d \alpha_g}\right) K_{fs} \exp(\alpha_g h_0) \qquad (14)$$

where r_d is the particular radius of the disc.

Sorptivity was determined at the early stage of the infiltration using the cumulative infiltration (i) as a function of square root of time (t = 5 minutes) as described by Bonsu (1993):

$$i = St^{1/2} \qquad (15)$$

Figure 3.3. Tension disc infiltrometer (Model 2800 soil moisture equipment corp. Santa Barbara, CA, USA)

3.10 Macro-porosity

Macro-porosity was determined using the following methods:

(i) From water retention curve by deducting the equilibrium volumetric water content at 0.1 m or 1 kPa (pores with diameter greater than 300 μm) from the saturated water content as described by Bonsu (1978). The size of the pores in unsaturated state can be determined through the so called hydraulic radius (r) of a section of pore space. The relationship between r and the capillary forces expressed as pressure head potential (h in m) is represented by the capillary rise equation Marshall and Holmes (1988):

$$h = \frac{2\gamma \cos \alpha}{\rho_w g r}, \qquad (16)$$

where r in µm is the equivalent cylindrical pore (hydraulic) radius related to the meniscus curvature (R) via the equation r = R cos. α, cos. α = 1 (as α = 0 for a wetted surface),

γ is the surface tension between water and air (at 30 °C = 0.0712 kg s^{-2}),

g is the acceleration due to gravity (9.81 m s^{-2}),

ρ_w is the density of water at 20 °C= 998 kg m^{-3}. Pore size diameters were determined by applying the capillary rise equation with respect to the soil water retention curves

(ii) From disc infiltrometer measurements as described by Buczko *et al*. (2006) by determining first the number of hydraulically active pores per unit area (N_m) using the Hagen-Pousseuille equation for laminar flow:

$$N_m = \frac{8\eta q_m}{\pi g \rho r_m^{\ 4}}, \qquad (17)$$

where η denotes the dynamic viscosity of water (taken here at 0.7982 g cm^{-1} s^{-1} for a temperature of 30 °C),

r_m is the minimum radius for macro pores (0.5 mm) and a unit hydraulic gradient were assumed,

q_m the difference between infiltration rates at 0 cm H_2O and -9 cm H_2O, according to the capillary theory (14), infiltration at tensions 12, 9 and 3 cm excluded from the flow process pores of equivalent diameter greater than 0.25, 0.33 and 1 mm, respectively.

The effective macro-porosity θ_m was calculated as:

$$\theta_m = N_m \pi r_m{}^2, \quad (18)$$

3.10.1 Chemical properties

3.10.1.1 pH

Soil pH was measured by means of pH meter (Eutech Instrument). Before the measurements, the pH meter was calibrated using buffer solutions of pH 4 and 7. pH water (actual acidity) was measured in a 1:2.5 soil-water (distilled water) suspension. Ten grams (10 g) of soil was weighed into a beaker and 25 mL of distilled water was added. The suspension was stirred mechanically and allowed to stand for 30 minutes and the pH in water was measured.

3.10.1.2 Soil organic matter

Organic matter content of soil for each treatment was determined by the method described by Walkley and Black (1934). Triplicate samples of each treatment were used in this determination which was carried out as follows: 2 g of soil was weighed in 500 mL Erlenmeyer flask and 10 mL of *0.1667 M* potassium dichromate ($K_2Cr_2O_7$) solution was added and the mixture stirred gently to disperse the soil. Twenty millilitres of concentrated (95%) H_2SO_4 added to the suspension which was shaken gently and allowed to stand for 30 minutes on an asbestos sheet. Thereafter, 200 mL of distilled water was added. Then 10 mL of concentrated (85%) orthophosphoric acid (H_3PO_4) and 1 mL of diphenylamine indicator were also added. The suspension was titrated with *1.0 M* $FeSO_4$ until the colour changed to blue and then to a pale green end-point. A blank was included and treated in the same way. The percentage organic matter (OC) was calculated as follow:

$$OC(\%) = (a-b)\times(\frac{0.5}{c})\times 1.33\times \frac{12}{4000}\times 100 \quad (19)$$

where a = volume of $FeSO_4$ added to the blank,

b = volume of $FeSO_4$ added to the soil sample,

c = weight of soil sample and 12/4000 is the milliequivalent weight of C in grams.

The percentage organic carbon was used to calculate percent (%) organic matter (OM) as follows:

$$OM(\%) = OC\times 1.724 \quad (20)$$

where 1.724 is a correction factor (van Bemmelan factor)

3.10.1.3 Total nitrogen

This was determined by the Kjeldahl digestion and distillation method as described by Bremner and Mulvaney (1982). A 5.0 g soil was put into a Kjeldahl digestion flask and 10 mL distilled water added and allowed to stand for 10 min to moisten. One spatula full of Kjeldahl catalyst (mixture of 1 part Selenium powder + 10 parts $CuSO_4$ + 100 parts Na_2SO_4) and 30 mL concentrated H_2SO_4 were added to the mixture and carefully mixed. The sample was digested on a Kjeldahl apparatus for 3 hours until clear and colourless digest was obtained. The volume of the solution was made up to 100 mL with distilled water in a 100 mL volumetric flask. A 10 mL aliquot of the solution was transferred to the distillation flask and 20 mL of 40% NaOH solution added followed by distillation. The distillate was collected over 4% boric acid in a 500 mL conical flask. Three drops of mixed indicator were added and the solution allowed standing for 4 minutes followed by titration with 0.1 *M* HCl solution. Traces of nitrogen in the reagents and water used were neutralized by carrying out a blank distillation and titration. Total nitrogen was calculated using the following equation:k2

$$\text{Total N (\%)} = \frac{14 \times (A - B) \times N \times 100}{1000 \times 0.5} \qquad (21)$$

where A= volume of standard solution used in the sample titration,

B= volume of standard HCl used in the blank titration,

N = normality of HCl,

0.5 = dilution factor (5 g x10 mL / 100 mL).

3.10.1.4 Soil available phosphorus

Soil available phosphorus was determined by the Bray No.1 method (Bray and Kurtz, 1945). Five gram of air-dried soil (2 mm sieved) was weighed into centrifuge tubes and 30 mL of Bray No.1 solution added. The tubes were then shaken for 5 min on a mechanical shaker, allowed to stand for 2 min and then centrifuged for 5 min at 3000 rpm. Ten millilitres (10 mL) of the clear supernatant solution (sample) was pipetted into a set of clean centrifuge tubes; 6 mL of distilled water and 1 mL of molybdate colour development reagent were added and mixed well. Two (2) mL of ascorbic acid solution was added and mixed thoroughly. Standard solutions containing 0, 1, 2, 4, 8 and 10 µg P mL^{-1} were also prepared and treated similarly. Percent transmittance (colour) was measured after six (6) minutes at a wavelength of 650 nm on a colorimeter (Jenway 6051 colorimeter) and the obtained values recorded. The percentage transmittance (T) values were first converted into absorbance using the formula: 2 - log T and a graph plotted using P standard solutions. The P concentration in the extract was obtained by comparing the results with the readings from the standard curve plotted:

$$\text{P (mg kg}^{-1}\text{soil)} = \frac{C \times Df}{ODW} \quad (22)$$

where, C= phosphorus concentration from the curve equation,

Df = dilution factor and ODW= the oven-dry weight of soil.

3.10.1.5 Exchangeable potassium

Exchangeable potassium was determined by the ammonium acetate (NH_4OAc) solution at pH 7 extraction method. Five grams (5 g) of air-dried and sieved (2 mm) soil was weighed into extraction plastic bottles with stopper and 50 mL of 1.0 *M* ammonium acetate extraction solution at pH 7 added. The suspension was shaken for 30 min on a mechanical shaker and the extract was filtered into reagent bottles through a Whatman No. 42 filter paper. The soil extract was diluted ten times for K determination by pipetting 5 mL into a 50 mL volumetric flask and adding 1 mL of 26.8% lanthanum chloride solution and diluting the content to the mark with 1 M NH_4OAc. Standard solutions of 0, 2, 4, 6 and 8 ppm K were also prepared and a standard curve was plotted after reading using flame photometer. The flame photometer reading for soil extract solutions was determined. K content was calculated as follows:

$$\text{K (mg / 100 g air-dried soil)} = \frac{\text{graph reading x 100 x Aliquot x Dilution}}{\text{weight of soil sample}} \quad (23)$$

3.10.1.6 Determination of total phosphorus and potassium in pearl millet leaf

One gram (1 g) of milled plant sample was weighed into ceramic crucibles arranged serially and placed in a cool muffle furnace and ashed at 500 °C over a period of 2 hours. This temperature was allowed to remain for an additional 2 hours. The samples were allowed to cool down in the oven. The crucibles were then removed, and 10 mL of aqua regia (Conc. HCl + 70% NHO_3) solution was added and the ashed sample was washed with distilled water into already numbered 50 mL centrifuge tubes. The suspensions were centrifuged at 3000 rpm for 10 minutes, then decanted and filtered using Whatman No. 42 filter paper into 100 mL volumetric flasks and made up to volume. The sample extracts were later transferred into 200 mL reagent bottles.

To determine phosphorus, 10 mL of the digest was measured into 50 mL volumetric flask and 10 mL of vanado-molybdate solution was added. The mixture was made up to volume with distilled water and allowed to stand undisturbed for 30 minutes for colour development. Standard curve was developed concurrently with P concentrations ranging from 0.0, 5.0, 10.0, 15.0, 20.0 mg P L^{-1}. The absorbance of the blank, control and the samples were read on the Jenway Colorimeter at the wavelength of 650 nm. A graph of absorbance versus concentration (mg kg^{-1}) was plotted. The blank and unknown standards were read and the mg kg^{-1} P was obtained by interpolation on the graph plotted from which concentrations were determined. P content (µg) in 1.0 g of plant sample = C x *Df*, P content in g in 100 g of plant sample,

$$P\ (\%) = \frac{C \times Df \times 100}{1000000} = \frac{C \times 1000 \times 100}{1000000} = \frac{C}{10} \qquad (24)$$

where, C = phosphorus concentration (µg mL^{-1}, as read from the standard curve,

Df = dilution factor, which is 100 x 10 = 1000, calculated as: 1 g of sample solution made up to 100 mL (100 times), 5 mL of the sample solution made up to 50 mL (10 times) and 1000000 = factor for converting µg to g.

Potassium content in the supernatant digest was determined using the Jenway flame photometer (PFP 7). Standard solutions of KH_2PO_4 with concentrations of 0, 200, 400, 600, 800 and 1000 mg L^{-1} were prepared and emissions read from the flame photometer. A graph of the emissions versus concentrations of the standards was plotted from which the K concentrations of the plant samples were calculated as follows:

K (µg) in 1 g of plant sample = C x df, K content in 100 g of plant sample,

$$\text{K (\%)} = \frac{C \times Df \times 100}{1000000} = \frac{C \times 100 \times 100}{1000000} = \frac{C}{100} \quad (25)$$

where, C = K concentration (µg mL^{-1}, as read from the standard curve,

df = dilution factor, which is 100 x 1 = 100, calculated as: 1 g of sample solution made up to 100 mL (100 times),

k21000000 = factor for converting µg to g.

3.11 Biomass yield

Millet was harvested in 10 x 10 m area located in the central part of each plot. The weight of both panicles and stubbles were determined separately after sun drying. The total stubble yield was determined and then converted into kg ha^{-1}. The total grain yield (kg ha^{-1}) was determined after threshing subsamples of panicles of known weight. A subsample of 5 kg of millet of panicles was taken from each treatment. These panicles were threshed using pestle and mortar, and winnowed to remove the grains and then weighed. The grain yield for each plot (in kg.100 m^{-2}) was determined and converted into kg ha^{-1}.

3.12 Simulation of millet grain and biomass yield using APSIM model

The Agricultural Production Simulation System (APSIM) was tested for its ability to simulate millet yield for the control and fertilizer treatments under the two types of farms of the on-farm evaluation of soil fertility restoration technologies at Karabédji, Niger. However, since the K module necessary to simulate the effect of K on millet growth has not yet been activated in APSIM version 7.6 and crop model such as DSSAT does not simulate P for millet, simulations were therefore carried out based on N and P rates in different treatments. Previous report (Bationo *et al*., 2007), showed no significant increase in both grain and total dry matter yields of pearl millet over five years from field experiments at Sadoré and Gobéri, Niger, from an experiment that was established to determine the relative importance of N, P and K fertilizers. Furthermore, K is even being omitted in the fertilizer micro-dosing recommended rate of 20 kg DAP fertilizer per ha (Tabo *et al*. 2005).

Additionally, pearl millet yields simulated using observed weather data obtained from the nearest meteorological station were compared to predicted yields using generated weather data of the study site.

3.12.1 Data set

Among the climatic parameters necessary to run the model for the study site only rainfall was available. Therefore, climatic data including rainfall, maximum and minimum temperatures, and solar radiation for 30 previous years were obtained from the nearest meteorological station located at Sadoré International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) which is 25 km away from Karabédji. Moreover, MarkSimGCM (CGIAR / CCAFS, 2014), a stochastic weather generating tool, was used to generate daily climatic data for 30 years for the study site using geographic coordinates. Crop management and yield data were collected over 2012 and 2013 growing seasons from the long-term on-farm soil fertility restoration trial. Both soil physical and chemical properties were also measured.

3.12.2 Simulation of millet grain and biomass yields

To predict millet grain and biomass yields for the 2012 and 2013 growing seasons, simulation was run from 1st May 2012 to 30th September 2013. The 'Manager' module of the APSIM model (version 7.6, build No. R3376, 2014) was set using the field operations employed for the control and fertilizer treatments. The field operations included sowing date; type, application mode and rate of fertilizer; date of fertilizer application and harvesting rule. The selected planting date was 1st June for each year, whereas band application was selected as mode of fertilizer application as no option was available for fertilizer micro-dosing in APSIM. Pearl millet cultivar "Haini Kirey" was used for the simulations. "Haini Kirey" is commonly used by farmers in the region. The phenological parameters of this variety (Appendix 3) for use in crop growth models were previously reported (Akponiké, 2008). The soil module components namely Water, SoilWater, SoilOrganicMatter, Analysis, Phosphorus and Initial Nitrogen, in the Niger-Sandy soil (Psammentic Paleustalf) profile characteristics (Akponiké, 2008), were adjusted, where necessary, to match with measured characteristics of treatments.

3.12.3 Model evaluation

The ability of the model to predict millet grain and biomass yields was evaluated using the Root Mean Square Error - RMSE (Loague and Green, 1991) and the d index of agreement (Wiltmott *et al*., 1985) described as follow:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \qquad (26)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i - \hat{O}| + |O_i - \hat{O}|)^2} \right] \qquad (27)$$

where S_i and O_i are the simulated and the observed respectively,

$\hat{O}$ the average of the observed values,

n is the number of observations,

RMSE and d are expected to be as close as possible to 0 and 1, respectively.

3.13 Socio-economic survey

A socio-economic survey was conducted between May and June 2013 to study the influence of farmers' socio-economic conditions on the fertility level of their fields.

3.13.1 Selection of respondents and sample size

The general census records and key informants were used to randomly select the respondents. Survey respondents consisted of both farmers who were involved in a long-term on-farm evaluation of soil fertility restoration technology and farmers who were not involved from Karabédji village, and four other neighbouring villages namely, Seké Koira Zeno, Seké Koira Tegui, Gobriko Béri and Gobriko Zanguina. This long-term trial, initiated since 1999, consisted of millet grown under three different rates of fertilizer micro-dosing and a control (no fertilizer) on 23 farmer's fields. These fertilizer rates were: 4 kg P ha^{-1} as NPK 15-15-15, 4 kg P ha^{-1} as DAP (Di ammonium phosphate), 4 kg P ha^{-1} as NPK 15-15-15 + 13 kg rock phosphate ha^{-1}, and 0 P ha^{-1}. The number of interviewed households included 16 out of the 23 farmers involved in the on-farm trial and 25 farmers not involved from Karabédji, and 15 from each of the four neighbouring villages, making a total of 101 households (Table. 3.1).

3.13.2 Data collection and processing

The survey was carried out as a semi-structured interview using a questionnaire of several questions on individual and household information. Farmer's resource endowment, soil fertility management practices, and farmers' view about farming-related constraints and opportunities, etc. For questions on farm income and inputs, farmers were asked to give a range to which they belong as respondents were hesitant in this regard in the questionnaire pretesting phase. For comparison purpose, between respondents, the total number of animals and birds possessed by a farmer was expressed as Tropical Livestock Unit (TLU), where one TLU is equivalent to 250 kg of biomass (FAO, 1986; Cecchi *et al.*, 2010). The conversion factors used were as follow: 0.7 for cattle, 0.5 for donkey, 0.10 for sheep and goat, and 0.01 for chicken.

The total quantity of yearly applied household manure was assessed by the number of transported manure. Where farmers solicited corralling from Fulani herdsmen to settle on their farms (during the dry season) for manuring, a compensation, in kind, is given such as 100 kg bag of millet, sorghum or maize to the herder. Therefore the equivalent value (in Fcfa) of the compensation given out by farmer was used to estimate the cost of manure.

Table 3.1. Villages used for socio-economic survey and the corresponding population and sample sizes

Village	Population	Non- project members	Project members	Total no. of households
Karabédji	6 000	25	16	41
Seké K. Tegui	2 000	15	0	15
Seké K. Zeno	1 500	15	0	15
Gob. Béri	1 800	15	0	15
Gob. Zanguina	1 900	15	0	15
Total	13 200	85	16	101

3.14 Statistical analyses

The data was processed and analysed using the Restricted Maximum Likelihood (REML) method of mixed model analysis in Genstat (9th Edition, 2007, Lawes Agricultural Trust) statistical package. The data comprised treatment and farm type as independent variables and farm as block. The model used is as follows**:**

Fixed component = Fertilizer + Type + Fertilizer x Type

Random component = Block + Main plot + residual

Y = Fertilizer + Type + Fertilizer *Type + Block + TP + E where Block, TP and E are random terms with variances σ_b, σ_{tp} and ε, respectively. Farms by farm type were samples from wider population of farms, and was therefore defined as random component.

The ante-dependence structure of order 1 was used to analyse data on total P and K which were taken by repeated measurements at different growth stages. Farm by growth stage was used as random term. Regression analyses were used to determine the degree of relationships existing between measured parameters. Natural log-transformed values were used for statistical analysis of data on infiltration measurements as reported by Reynolds (2000).

For socio-economic data, factor analysis in SPSS (16^{th} edition) was used to identify key variables that explained most of the variance observed in the survey data. The key variables have highest score coefficients on each of the extracted components. Respondents with similar characteristics were then grouped using Similarity Matrix and Single Linkage hierarchical cluster analysis methods in Genstat (version 9.2) and soil fertility management practices were compared among the groups. Cross tabulation in SPSS was used to show the relationship between variables.

CHAPTER FOUR

4.0 RESULTS

This section deals with the results of the study. The treatments comprised the following rates of fertilizer application and farm types:

- **Fertilizer treatments**: Control, Di-ammonium phosphate (DAP), NPK 15-15-15 and NPK 15-15-15 + Rock phosphate.
- **Farm type**: Top and Bottom

4.1 Soil physical and hydrological properties

4.1.1 Soil particle size analysis

The particle size analysis of the 0-20 cm soil depth of top and bottom farm types (Table 4.1) showed that over 90% of the particles were sand-sized whereas silt-sized particle represented less than 2%. Clay-sized particles in the top and bottom farm types constituted 5.4 and 6% of the particles, respectively. The texture of the soils at both sites was sand.

Table 4.1. Soil particle size distribution on top and bottom farm types (0-20 cm)

Particle size*	Farm type	
	Top	Bottom
Sand (g kg^{-1})	924 (±7.9)	927 (±8.7)
Silt (g kg^{-1})	18 (±9.1)	16 (±6.6)
Clay (g kg^{-1})	60 (±19.7)	54 (±17.7)
Textural class	Sand	Sand

*Values are average of four replicates; values in parenthesis represent ± standard deviation.

4.1.2 Soil specific volume

Soil specific volume ranged from 0.592 to 0.609 m^3 Mg^{-1} and from 0.593 to 0.632 m^3 Mg^{-1} in the uppermost 0-10 cm soil layer for top and bottom farm types respectively (Table 4.2). Similar ranges were observed in the 10-20 cm depth. However, no significant effect ($P < 0.05$) of fertilizer and farm type on soil specific volume was observed (Appendix 1.1). The random term farm by farm type accounted only for 11% of the variability in soil specific volume among fertilizer application and farm types.

4.1.3 Air capacity

There was no significant effect ($P > 0.05$) of the different fertilizer treatments, farm types and soil depths on soil air capacity (Table 4.3). Air capacity ranged from 0.171 to 0.186 $m^3 m^{-3}$ and from 0.177 to 0.186 $m^3 m^{-3}$ in the 0-10 cm soil depth for the top and bottom farm types respectively. Similar values were also recorded in the 10-20 cm soil layer (Table 4.3.). Farm by farm type accounted for 61% of the variability in air capacity (Appendix 1.2).

4.1.4 Soil macro-porosity

The effects of fertilizer application and farm type on soil macro-porosity determined from soil water retention curve (SWRC) and from tension disc infiltrometer methods are shown in Tables 4.4 and 4.5, respectively.

Statistically, significant effect ($P < 0.05$) on macro-porosity was observed only between fertilizer x depth interaction with the SWRC macro-porosity determination method (Appendix 1.3). Lower values of macro-porosity were consistently recorded in the 10-20 cm depth than in the top soil (Table 4.4).

Similar trend was observed in soil macro-porosity determined using disc infiltrometer method (Table 4.5). Generally, soil macro-porosity did not vary much among fertilizer treatments and farm types with the two methods. Values ranged from 0.0044 to 0.0106 $m^3 m^{-3}$ in the farm type and from 0.0044 to 0.0123 $m^3 m^{-3}$ in the bottom farm type with the SWRC method. For the infiltrometer method, values ranged from 0.0049 to 0.0087 m^3 m^{-3} in the top farm and 0.0071 to 0.0093 m^3 m^{-3} in the bottom type. For both methods, relatively higher values were found in the subsoil (10-20 cm) than in the top soil. For example, values were obtained under NPK + TRP treatment were 20% higher in the sub soil than in the top soil with respect to the disc infiltrometer method (Table 4.5). In the SWRC method, plots treated with NPK + TRP produced values which were 56% higher in the sub soil than in the top soil. The random term farm by farm type did not account for the observed variability in this parameter (Appendix 1.3 and 1.4).

4.1.5 Soil water content at field capacity (FC) and relative field capacity (RFC)

Farm types and soil depths interacted significantly ($P < 0.05$) to affect soil water content retained at field capacity (Table 4.6). Higher values of water content at field capacity were consistently obtained in the 0-10 cm soil layer compared to the 10-20 cm soil depth in the top farm type. Soil water content was considerably higher at 0-10 cm and 10-20 cm under both top and bottom farm types. Forty percent (40%) of the variance in FC were accounted for by farm by farm type (Appendix 1.5).

Soil relative field capacity was not significantly ($P > 0.05$) influenced by the different fertilizer treatments, farm types and soil depths (Table 4.7). However, relatively higher values of RFC were observed in top farms compared to bottom farms. Farm by farm type accounted for 46% of the observed variability in RFC (Appendix 1.6).

Table 4.2. Effects of fertilizer application and farm type on soil specific volume

Farm Type	Fertilizer type	Soil specific volume (m^3 Mg^{-1})	
		0-10 cm	10-20 cm
Top	Control	0.592	0.609
	DAP	0.599	0.609
	NPK151515	0.609	0.620
	NPK151515+TRP	0.603	0.607
Bottom	Control	0.632	0.608
	DAP	0.601	0.610
	NPK151515	0.593	0.591
	NPK151515+TRP	0.596	0.607
χ^2 pr.		ns	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.3. Effect of fertilizer application and farm type on soil air capacity at 0-10 cm and 10-20 cm depths

Farm Type	Fertilizer type	Soil air capacity (m^3 m^{-3})	
		0-10 cm	10-20 cm
Top	Control	0.171	0.174
	DAP	0.172	0.178
	NPK151515	0.181	0.182
	NPK151515+TRP	0.186	0.175
Bottom	Control	0.180	0.176
	DAP	0.186	0.176
	NPK151515	0.177	0.176
	NPK151515+TRP	0.184	0.185
χ^2 pr.		ns	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.4. Effects of fertilizer application and farm type on macro-porosity determined from soil water retention curve

Farm type	Fertilizer type	Macro-porosity ($m^3 m^{-3}$)	
		0-10 cm	10-20 cm
Top	Control	0.0076	0.0086
	DAP	0.0057	0.0106
	NPK151515	0.0105	0.0074
	NPK151515+TRP	0.0092	0.0099
Bottom	Control	0.0077	0.0106
	DAP	0.0082	0.0100
	NPK151515	0.0123	0.0044
	NPK151515+TRP	0.0087	0.0136
χ^2 pr. Fertilizer x Depth		0.049	
s.e.d. Fertilizer x Depth		0.0011	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.5. Effects of fertilizer application and farm type on macro-porosity determined from disc infiltration measurements

Fertilizer type	Macro-porosity ($m^3 m^{-3}$)	
	Top	Bottom
Control	0.0087	0.0096
DAP	0.0069	0.0074
NPK151515	0.0049	0.0071
NPK151515+TRP	0.0074	0.0089
χ^2 pr.	ns	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.6. Effects of fertilizer application and farm type on soil water content at field capacity

Farm type	Fertilizer type	Soil water content (m^3 m^{-3})	
		0-10 cm	10-20 cm
Top	Control	0.149	0.129
	DAP	0.159	0.141
	NPK151515	0.145	0.128
	NPK151515+TRP	0.145	0.152
Bottom	Control	0.123	0.147
	DAP	0.130	0.134
	NPK151515	0.141	0.138
	NPK151515+TRP	0.130	0.126
χ^2 pr. Farm type x Depth		0.040	
s.e.d. Farm type x Depth		0.012	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer; multiply means by 100 mm to convert to mm.

Table 4.7. Effects of fertilizer application and farm type on soil relative field capacity

Farm type	Fertilizer type	Soil relative field capacity	
		0-10 cm	10-20 cm
Top	Control	0.462	0.427
	DAP	0.479	0.441
	NPK151515	0.442	0.414
	NPK151515+TRP	0.438	0.464
Bottom	Control	0.409	0.458
	DAP	0.412	0.438
	NPK151515	0.447	0.442
	NPK151515+TRP	0.415	0.408
χ^2 pr.		ns	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

4.1.6 Field saturated hydraulic conductivity (Kfs) and soil sorptivity

The results of saturated hydraulic conductivity are shown in Figure 4.1. No significant difference in saturated hydraulic conductivity (K_{fs}) was found between both fertilizer application and farm types. Very low values of K_{fs} and variability were obtained in all the treatments.

Soil sorptivity (Figure 4.2) was not also affected by fertilizer application and farm type. However, sorptivity decreased with increase in matric suction. The values ranged from about 1.5 cm $S^{-1/2}$ at the highest matric suction (-1.2 kPa) to 21 cm $S^{-1/2}$ at lowest pressure (- 0.01 kPa).

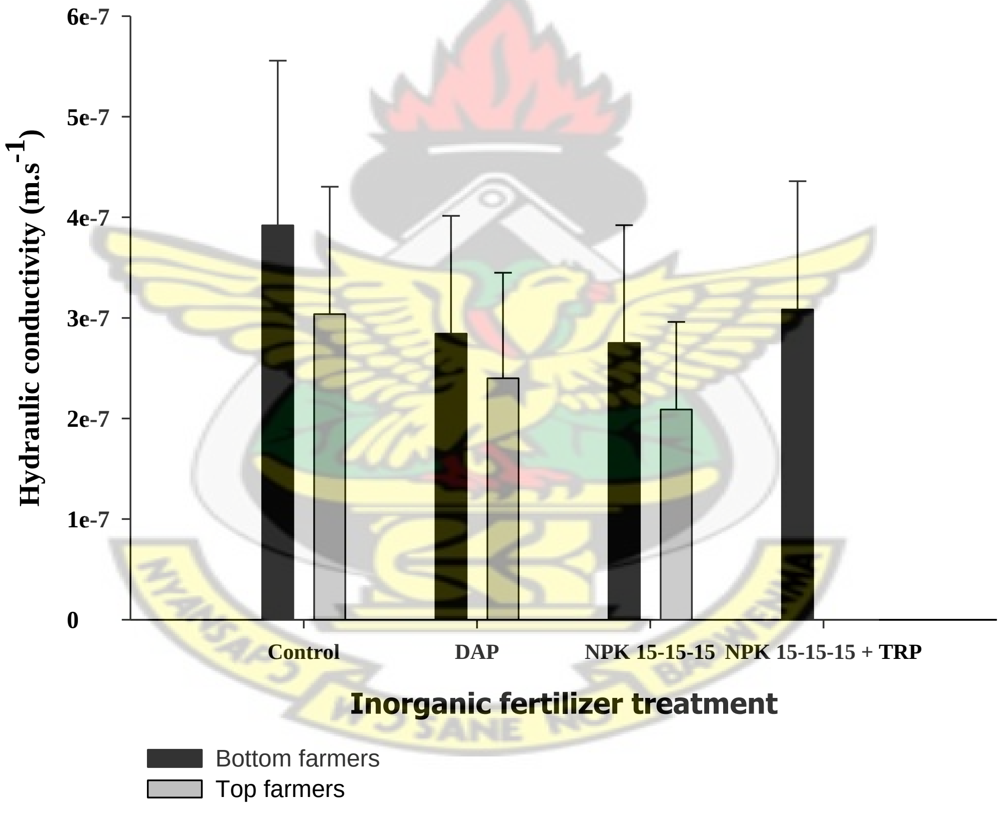

Figure 4.1 Field saturated hydraulic conductivity as affected by fertilizer application and farm type (Bars represent standard error)

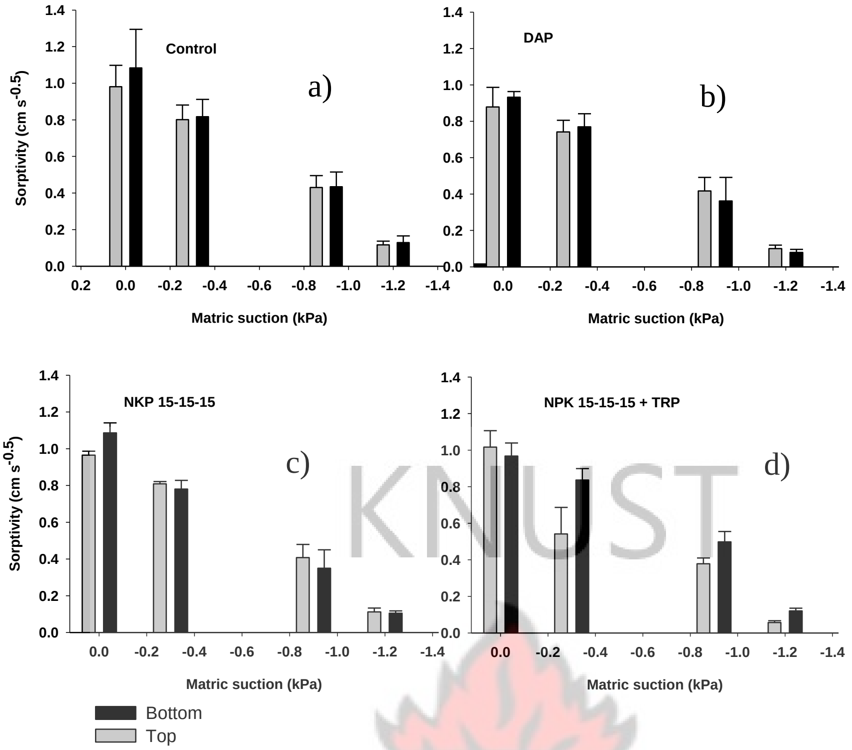

Figure 4.2. Soil sorptivity for the control (a), DAP (b), NPK 15-15-15 (c) and NPK 15-15-15 + TRP (d) at - 1.2, - 0.9, - 0.3 and - 0.001 kPa matric suctions as affected by fertilizer treatment and farm type.

4.1.7 Soil structural stability index

The result of the analysis of the water drop soil stability index is shown in Table 4.8. The interaction between fertilizer treatments and farm type was significant (P = 0.055) in soil structural stability index. Higher values of the index were observed in top farm type compared to bottom farm type (Table 4.8). For example, aggregates under DAP were 39% more stable in the top farm type than in the bottom farm type. Similarly, stability index under NPK 15-15-15 + TRP treatment was 21% higher in the top farm type than in the top bottom type. The control treatment consistently recorded the lowest values in both farm types. Farm by farm type accounted for 54% of the variability observed in the structural stability index (Appendix 1.7).

Table 4.8. Effect of fertilizer application and farm type on the stability index of soil aggregates (water drop method)

Fertilizer type	Soil aggregate stability (mL of water per aggregate)	
	Top farm	Bottom farm
Control	3.66	2.89
DAP	4.18	3.01
NPK151515	4.98	2.66
NPK151515+TRP	4.13	3.40
χ^2 pr. Farm type x Fertilizer	0.055	
s.e.d. Farm type x Fertilizer	0.77	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

4.1.8 Dexter soil physical quality index (S)

The effects of fertilizer application, farm type and soil depth on the Dexter soil physical quality “S” are shown in Table 4.9. Significant difference (P < 0.05) in S was observed only between soil depths (Appendix 1.8). As expected, higher values were observed in the top soil (0-10 cm) than in the subsoil (10-20 cm). The values were 4-6 times higher in the former than in the latter. Generally, control treatments had the lowest values in both farm types while NPK 15-15-15 + TRP had consistently produced the highest values. All observed values were far above the 0.035 which was set as critical value by Dexter.

Table 4.9. Effects of fertilizer application and farm type on Dexter soil physical quality index

Farm type		Soil physical quality index	
	Fertilizer type	0-10 cm	10-20 cm
Top	Control	0.087	0.014
	DAP	0.102	0.015
	NPK151515	0.097	0.016
	NPK151515+TRP	0.105	0.016
Bottom	Control	0.087	0.015
	DAP	0.081	0.019
	NPK151515	0.096	0.015
	NPK151515+TRP	0.109	0.013
χ^2 pr. Depth		0.001	
s.e.d. Depth		0.004	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

4.1.9 Plant water availability

The interaction between farm type, fertilizer treatment and soil depth was only significantly at P = 0.06 (Table 4.10). The observed values ranged from 10.6 to 11.7 mm and from 12.8 to 14.3 mm for bottom and top farm types respectively, in the 0-10 cm layer. Treatment means were lowest in the control of the top farm 10-20 cm layer and in the bottom farm 0-10 cm layer. Generally, lower values were obtained in the bottom farm type than the top farm type (Figure 4.3). Also lower values were obtained in the 10-20 cm than the 0-10 cm soil layer for the two farm types. The random term farm by farm type accounted for 43% of the variability in plant available water (Appendix 1.9).

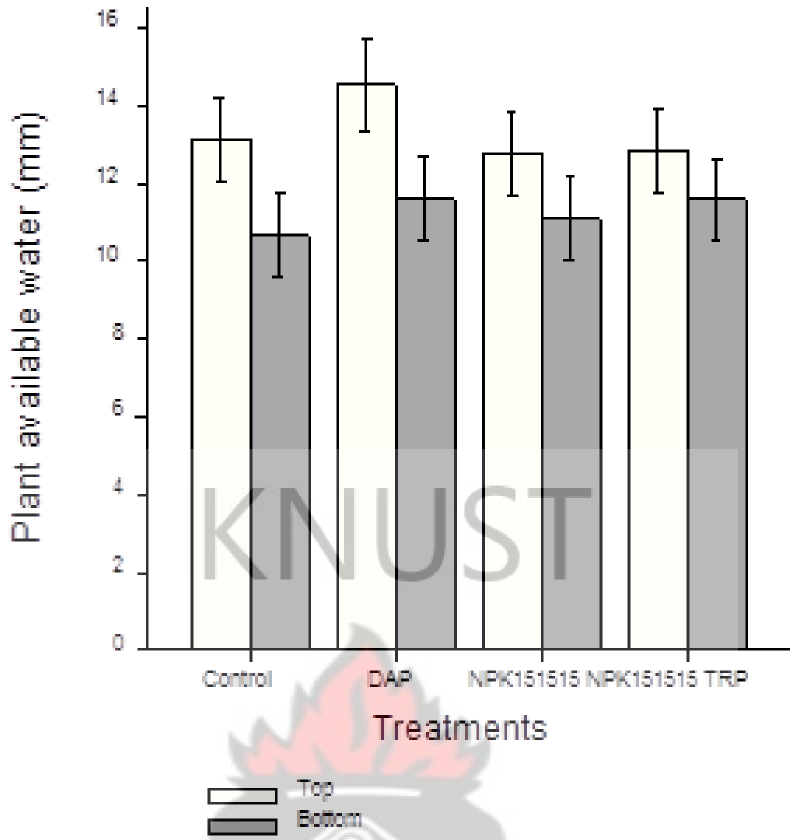

Figure 4.3. Plant available water content as affected by fertilizer treatment and farm type in the 0-10 cm layer. Error bars represent ± s.e.d.

Table 4.10. Effects of fertilizer application and farm type on plant available water

Farm Type	Fertilizer type	Plant available water (mm)	
		0-10 cm	10-20 cm
Top	Control	13.1	10.3
	DAP	14.3	12.1
	NPK151515	13.0	10.7
	NPK151515+TRP	12.8	13.4
Bottom	Control	10.6	12.5
	DAP	11.6	11.2
	NPK151515	11.7	10.6
	NPK151515+TRP	11.4	09.8
χ^2 pr. Farm type x Fertilizer x Depth		0.057	
s.e.d. Farm type x Fertilizer x Depth		1.5	

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer.

The fitted soil moisture retention characteristic curves, of the various fertilizer treatments in the 0-10 and 10-20 cm layers (Figure 4.4 and 4.5), exhibited changes in soil water content from -1 to -1500 kPa soil matric suctions. The shapes of the curves did not change significantly with the various treatments but generally higher values were obtained in the top farms (especially in the 0-10 cm layer) compared to the bottom farms. Significant positive correlation was found between plant available water and soil physical quality index (Figure 4.6).

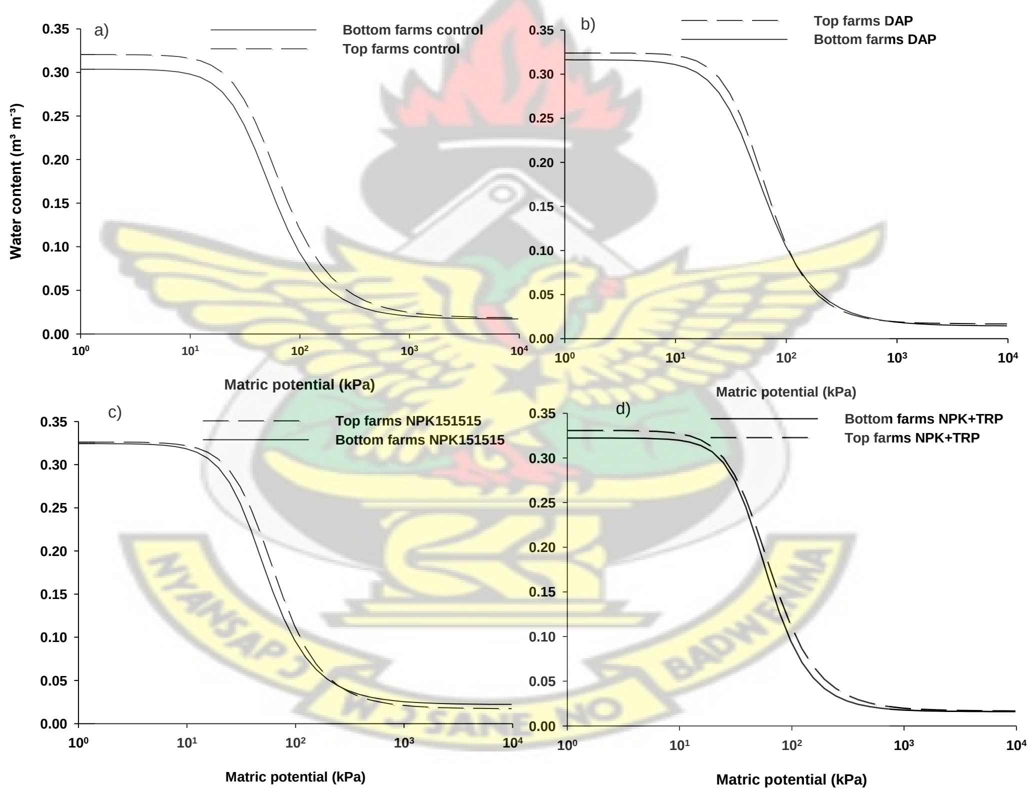

Figure 4.4. **S**oil water retention characteristics (fitted), (a) for control, (b) DAP, (c) NPK 15-15-15 and (d) NPK 15-15-15 + TRP treatments, as affected by fertilizer application and farm type at 0-10 cm depth. Multiply values in Y axis by 100 mm to convert to mm.

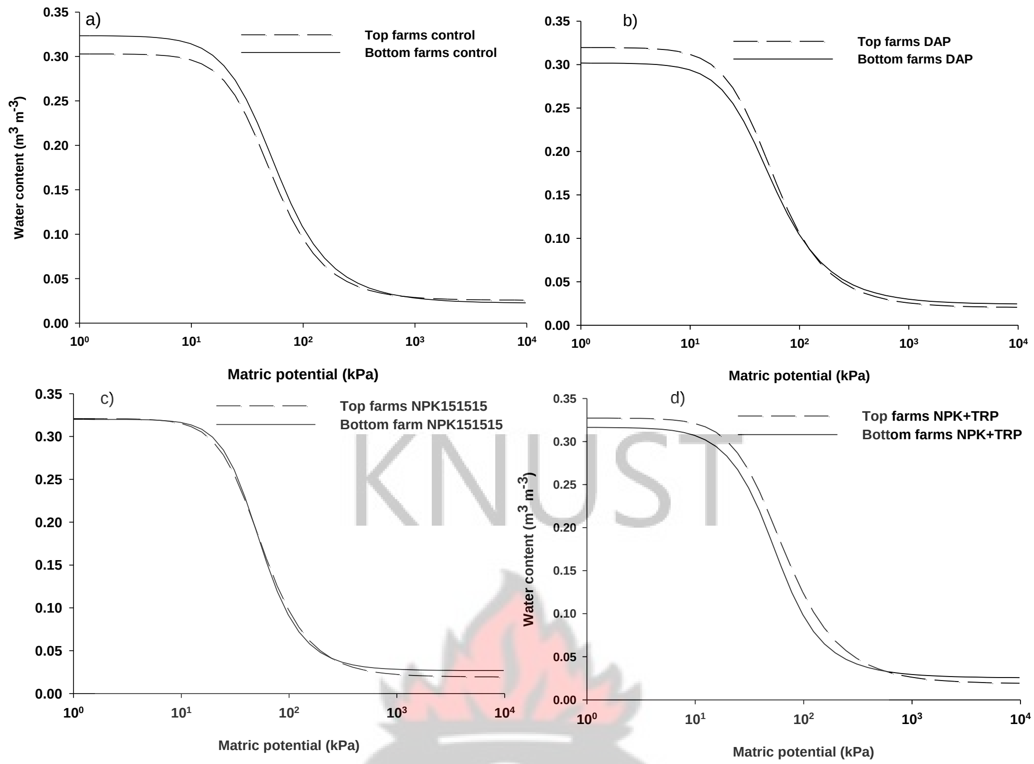

Figure 4.5. Soil water retention characteristics (fitted), (a) for control, (b) DAP, (c) NPK 15-15-15 and (d) NPK 15-15-15 + TRP treatments, as affected by fertilizer application and farm type at 10-20 cm depth. Multiply values in Y axis by 100 mm to convert to mm.

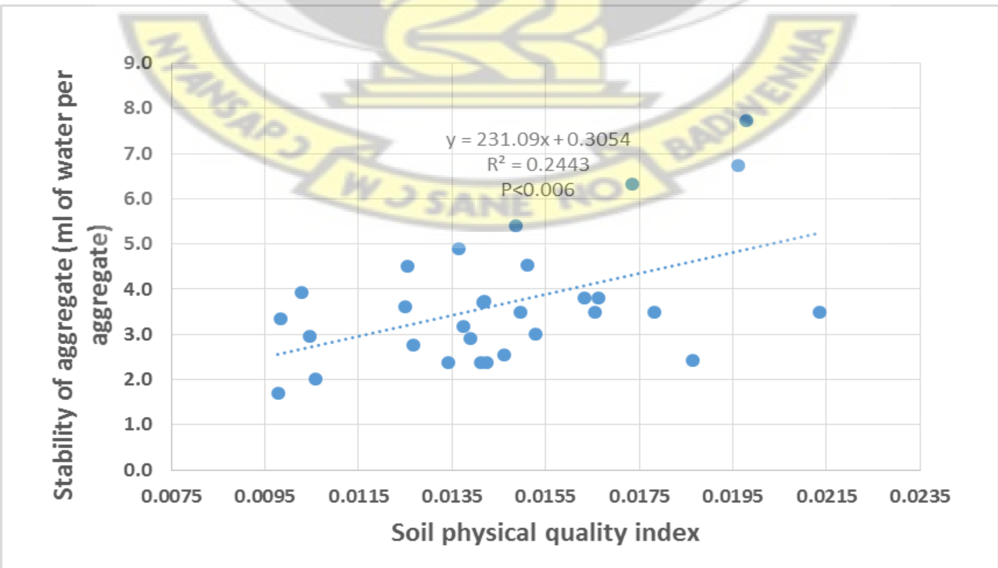

Figure 4.6. Relationship between stability of aggregate and soil physical quality index

4.2 Soil chemical properties

4.2.1 Soil pH

The effects of inorganic fertilizer application and farm type on soil pH are shown in Tables 4.11 and 4.12. Soil pH changed significantly ($P < 0.001$) with time of sampling during 2012 growing season but no significant ($P > 0.05$) difference was observed between fertilizer treatments and farm types (Appendix 1.10 and 1.11). However, the lowest pH values were observed in the control compared to treated-plots in both farm types. Similarly in 2013, no significant difference was obtained between the fertilizer application and farm types (Appendix 1.11). The difference in farm by farm type played a major role in the variability of soil pH as it accounted for 50% and 44% of variance in 2012 and 2013, respectively (Appendix 1.10 and 1.11).

4.2.2 Soil organic carbon content (OC)

Soil organic carbon C varied from 0.099% to 0.115% in top farm type and from 0.097% to 0.103% in bottom farm type in 2012 (Table 4.13) and from 0.116% to 0.132 in top farm and from 0.110% to 0.126 in bottom farm type (Table 4.14). There was no significant ($P > 0.05$) effect of fertilizer application and farm type on OC during both 2012 and 2013 seasons (Appendix 1.12 and 1.13). However, lower OC content values were generally observed in the control treatment compared to treated plots and in bottom farm compared to top type. The OC content of both farm types were generally low in both years of this study. The random term 'farm by farm type' accounted for only 10% of the variance in soil OC content in both 2012 and 2013 seasons (Appendix 1.12 and 1.13).

4.2.3 Soil total nitrogen, available phosphorus and exchangeable potassium contents

Soil total nitrogen content did not vary much among fertilizer application and farm types (Tables 4.15 and 4.16). Relatively, higher values of total N were recorded on top farms than the bottom farm type in both years. Farm by farm type did not account for any variability in soil total nitrogen content in 2012 (Appendix 1.14) but accounted for 40% of the variance in 2013 (Appendix 1.15).

Like total N, soil available phosphorus content was generally very low (Table 4.17). The values varied from 2.51 mg kg^{-1} in control plots to 3.62 mg kg^{-1} in NPK 15-15-15 + TRP treated plots in top farm and from 2.85 mg kg^{-1} in NPK 15-15-15 plots to 3.29 mg kg^{-1} in NPK 15-15-15 + TRP treated plots in the bottom farm type (Table 4.17). Similarly, low available phosphorus values were obtained in 2013 (Table 4.18). No significant ($P > 0.05$) difference in soil available phosphorus content was observed among fertilizer application and farm types in the two growing seasons (Appendix 1.16 and 1.17). Farm by farm type contributed by 2% and 27% in 2012 and 2013 respectively to the variability in available phosphorus content among the fertilizer application and farm types (Appendix 1.16 and 1.17).

Soil exchangeable potassium was found to be significantly ($P < 0.001$) influenced by time of sampling only (Tables 4.19). Higher values were consistently obtained before the growing season than after the season in both farm type. In general higher values were obtained in top compared to bottom farm type. ‘Farm by farm type’ accounted for 84% of the variability in soil exchangeable K in 2012 and 67% in 2013 (Appendix 1.18 and 1.19). Significant positive correlation was found between the aggregate stability index of water drop method and exchangeable K content (Figure 4.7).

Table 4.11. Effects of fertilizer application, farm type and time of sampling and interactions on soil pH in 2012

Fertilizer type	Soil pH*			
	Top farm		Bottom farm	
	Before	After	Before	After
Control	5.43	5.04	5.71	4.92
DAP	5.74	5.14	5.63	5.00
NPK151515	5.81	5.10	5.66	4.96
NPK151515+TRP	5.61	5.13	5.69	4.97
χ^2 pr. Time				< 0.001
s.e.d. Time				0.076

*Treatment means are average of four replicates; before and after the growing season are time of sampling; pH water; DAP = Di-ammonium phosphate fertilizer

Table 4.12. Effects of fertilizer application, farm type and interactions on soil pH water in 2013

Fertilizer type	Soil pH*	
	Top farm	Bottom farm
Control	5.97	5.84
DAP	5.95	5.91
NPK151515	6.08	5.84
NPK151515+TRP	6.09	5.86
χ^2 pr.		ns

*Treatment means are average of four replicates; pH water; DAP = Di-ammonium phosphate fertilizer

Table 4.13. Effects of fertilizer application, farm type and time of sampling on organic carbon (2012)

Fertilizer type*	Organic carbon content (%)	
	Top	Bottom
Control	0.099	0.097
DAP	0.115	0.097
NPK151515	0.111	0.103
NPK151515+TRP	0.112	0.100
χ^2 pr.		Ns

*Treatment means are average of four replicates, depth = 0-20 cm; DAP = Di-ammonium phosphate fertilizer

Table 4.14. Effects of fertilizer application and farm type on soil organic carbon content (2013)

Fertilizer type*	Organic carbon content (%)	
	Top farm	Bottom farm
Control	0.111	0.116
DAP	0.123	0.132
NPK151515	0.126	0.120
NPK151515+TRP	0.110	0.124
χ^2 pr.		Ns

*Treatment means are average of four replicates; depth = 0-20 cm; DAP = Di-ammonium phosphate fertilizer

Table 4.15. Effects of fertilizer application, farm type and interactions on soil total nitrogen content in 2012

Fertilizer type	Total nitrogen content	
	Top farm	Bottom farm
Control	0.0231	0.0187
DAP	0.0257	0.0219
NPK151515	0.0189	0.0259
NPK151515+TRP	0.0236	0.0205
χ^2 pr.		ns

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.16. Effects of fertilizer application, farm type and interactions on soil total nitrogen content in 2013

Fertilizer type	Total nitrogen content (%)	
	Top farm	Bottom farm
Control	0.0191	0.0183
DAP	0.0187	0.0172
NPK151515	0.0176	0.0176
NPK151515+TRP	0.0187	0.0183
χ^2 pr.		ns

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.17. Effects of fertilizer application, farm type and interactions on soil available phosphorus content in 2012

Fertilizer type	Available phosphorus (mg kg^{-1}soil)	
	Top	Bottom
Control	2.51	3.62
DAP	2.63	3.29
NPK151515	3.30	2.85
NPK151515+TRP	3.62	3.29
χ^2 pr.		ns

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.18. Effects of fertilizer application, farm type and interactions on soil available phosphorus content in 2013

Fertilizer type	Available phosphorus (mg kg^{-1}soil)	
	Top farm	Bottom farm
Control	2.46	2.81
DAP	2.46	2.67
NPK151515	2.56	2.46
NPK151515+TRP	2.26	2.84
χ^2 pr.		ns

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.19. Effects of fertilizer application, farm type and interactions on soil exchangeable potassium content in 2012

Fertilizer type	Exchangeable potassium (cmol kg^{-1} soil)			
	Top farm		Bottom farm	
	Before	After	Before	After
Control	0.180	0.124	0.116	0.085
DAP	0.156	0.120	0.115	0.064
NPK151515	0.165	0.120	0.102	0.083
NPK151515+TRP	0.150	0.121	0.106	0.079
χ^2 pr.				< 0.001
s.e.d. Time				0.020

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

Table 4.20. Effects of fertilizer application, farm type and interactions effects on soil exchangeable potassium content in 2013

Fertilizer type	Exchangeable potassium (cmol kg^{-1} soil)	
	Top farm	Bottom farm
Control	0.144	0.081
DAP	0.133	0.097
NPK151515	0.134	0.098
NPK151515+TRP	0.136	0.124
χ^2 pr.		ns

*Treatment means are average of four replicates; DAP = Di-ammonium phosphate fertilizer

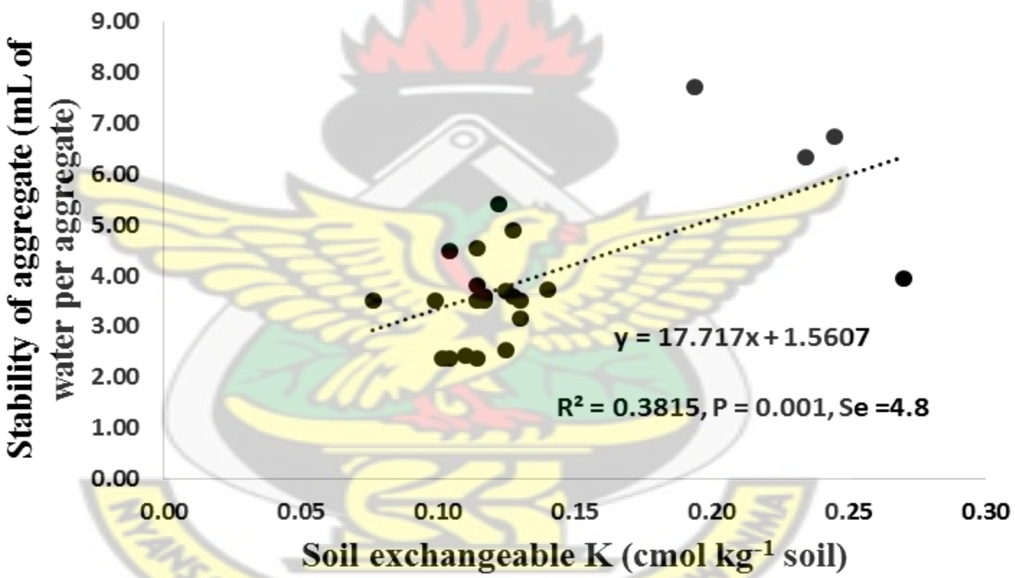

Figure 4.7. Relationship between stability of aggregate and soil exchangeable K content

4.3 Total phosphorus and potassium concentrations in pearl millet leaves

4.3.1 Total phosphorus concentration in millet leaf

Leaf P content was significantly (P = 0.027) influenced by time of sampling (growth stages) and growth stages x farm type interaction in 2012 (Appendix 1.20). The concentration of total phosphorus in millet leaf generally decreased with growth stage. The lowest values were recorded during the maturity stage in both farm types (Figure 4.8 and Figure 4.9) while the highest values were recorded during the tillering stage. Similar trend was observed in 2013 (Appendix 1.21). Total phosphorus level in millet leaf varied significantly ($P < 0.05$) with growth stage and growth stages x farm type interaction (Appendix 1.21). However, in the top farms, the highest values were recorded during the flowering stage. The control treatment generally recorded the lowest values compared to fertilizer amended plots during the tillering and the flowering stages in the two farm types (Figure 4.10 and Figure 4.11). There was also higher leaf P concentration at flowering stage in top farm compared to bottom farm type. The random term 'farm by growth stages' accounted for the variability observed in total phosphorus concentration in millet leaves among fertilizer treatments and farm types by 36% of in 2012 and by 9% only in 2013 (Appendix 1.20 and 1.21).

4.3.2 Total potassium content of millet leaves

This parameter was significantly ($P < 0.05$) influenced by fertilizer application and growth stages and their interactions (Appendix 1.22). Lowest values of K were recorded during the maturity stage whereas the highest values were generally recorded during the flowering stage in the two farm types (Figure 4.12 and Figure 4.13). Significantly lower ($P < 0.05$) values were recorded in the control than the DAP, NPK 15-15-15 and NPK 15-15-15 + TRP (Figure 4.12 and Figure 4.13) on both types of farms. Higher levels of K were generally recorded in top farm type than the bottom farm type. The random term 'farm by growth stage' accounted for 48% variation in leaf K concentration among fertilizer treatments and farm types (Appendix 1.22).

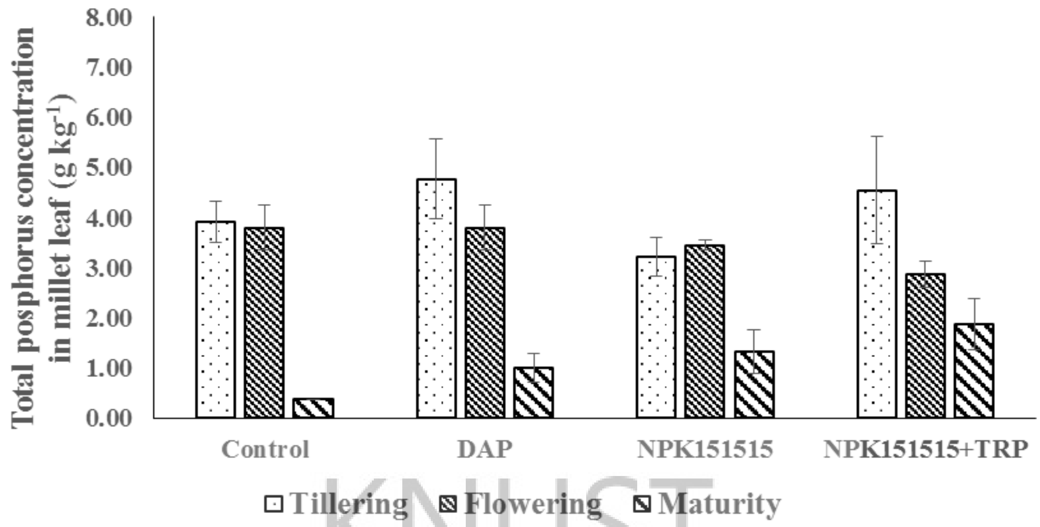

Figure 4.8. Mean total phosphorus concentration in leaf at different growth stages of millet under fertilizer treatment in top farm type in 2012. Error bars represent ± standard error.

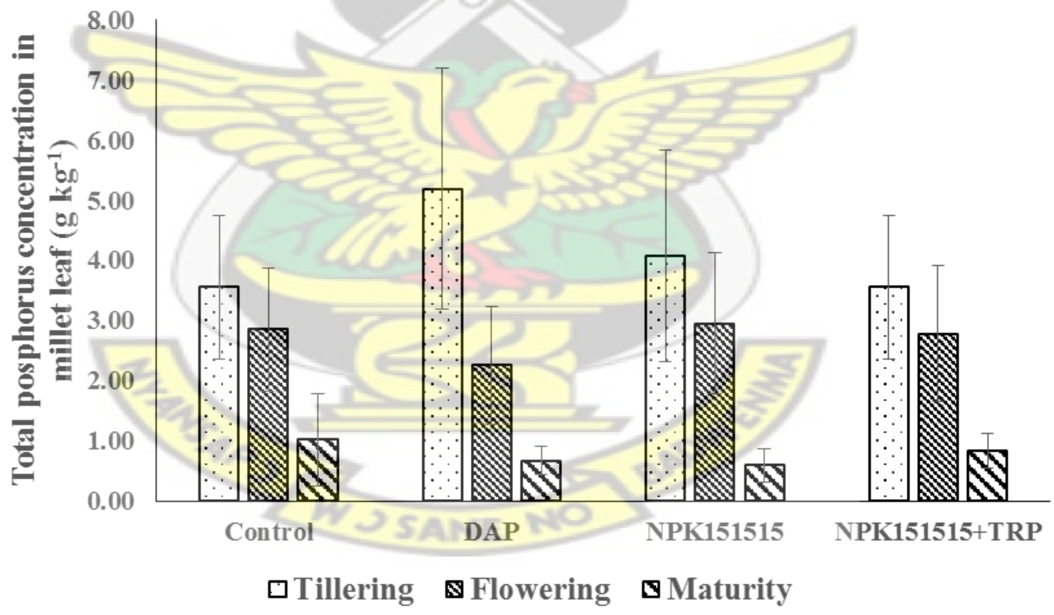

Figure 4.9. Mean total phosphorus concentration in millet leaf at different growth stages of millet under fertilizer treatment in bottom farm type in 2012. Error bars represent ± standard error.

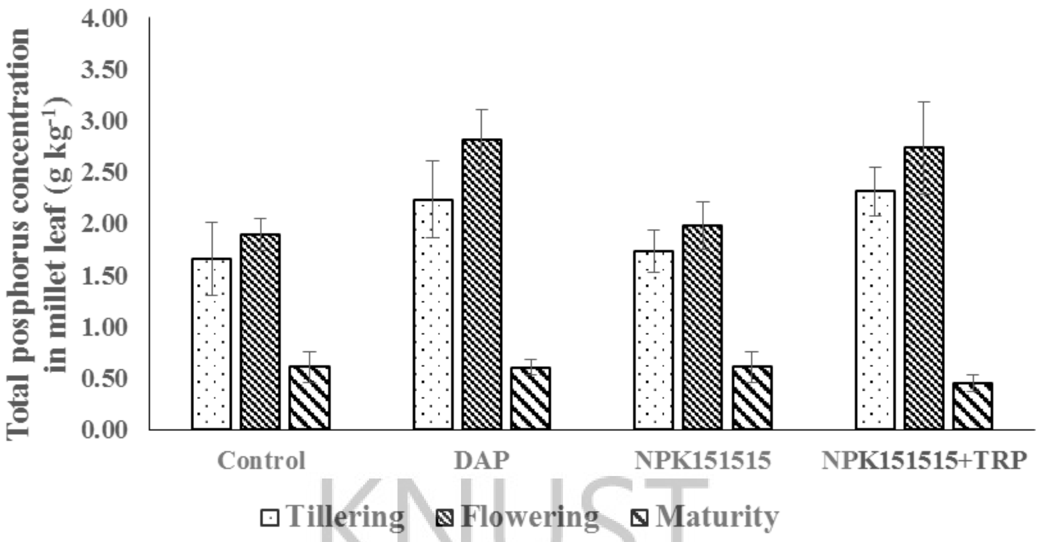

Figure 4.10. Mean total phosphorus concentration in leaf at tillering, flowering and maturity stages of millet under fertilizer treatment in top farm type (2013). Error bars represent ± standard error.

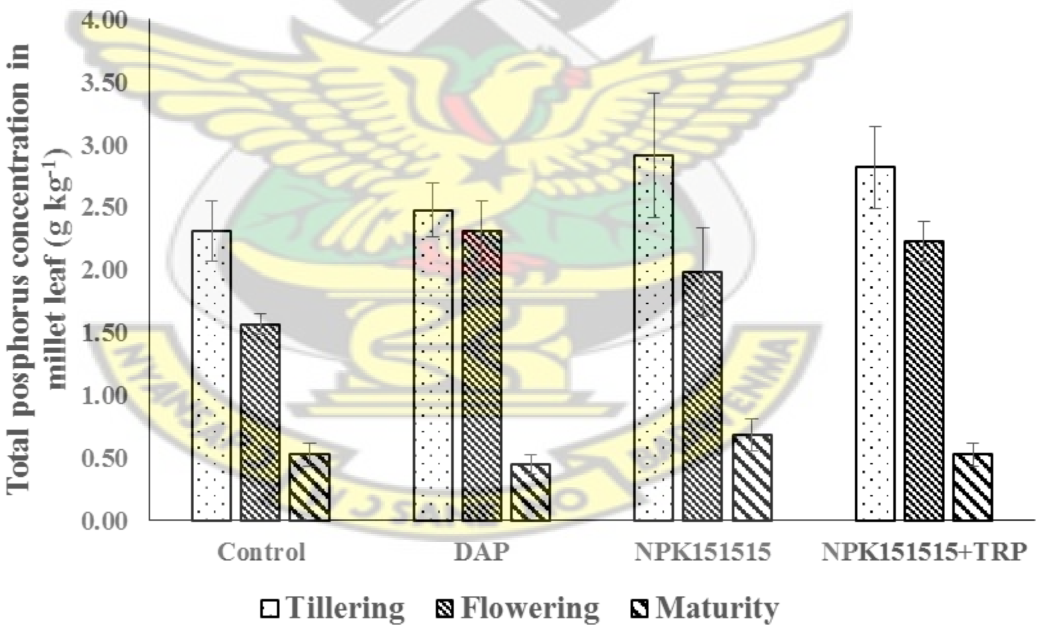

Figure 4.11. Mean total phosphorus concentration in leaf at tillering, flowering, and maturity stages of millet under fertilizer treatment in bottom farm type in 2013. Errors bar represent ± standard error.

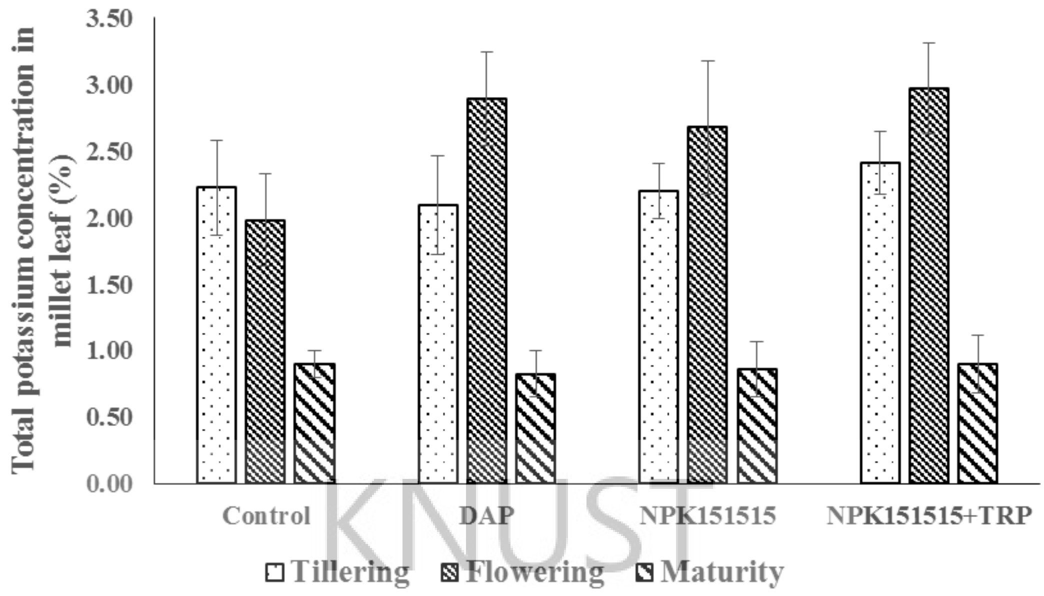

Figure 4.12. Mean total potassium level in leaf at tillering, flowering and maturity stages of millet under fertilizer treatment in top farm type. Error bars represent ± standard error.

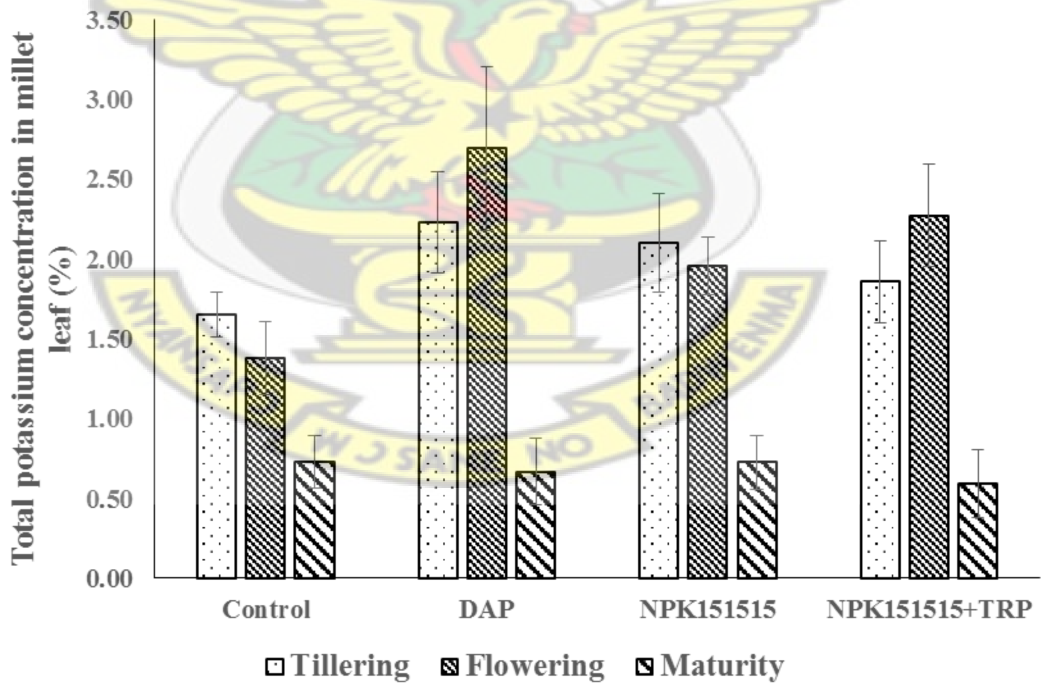

Figure 4.13. Mean total potassium concentration in leaf at tillering, flowering and maturity stages of millet as affected by fertilizer treatment in bottom farm type. Errors bar represent ± standard error.

4.4 Pearl millet grain and stubble yields

Inorganic fertilizer application and farm type interaction significantly affected ($P < 0.05$) millet grain yield (Table 4.21; Appendix 1.23) in 2012 growing season. Treatment NPK 15-15-15 + TRP recorded the highest grain yield followed by NPK 15-15-15 and DAP in both farm types. However, the increase in grain yield in treated plots over the control was much more pronounced in top farmers compared to bottom farmers (Figure 4.14). Millet grain yield recorded on top farms were more than two fold those recorded on bottom farms. The random term 'farm by farm type' accounted for 93% of the variations in millet grain yield in the 2012 growing season (Appendix 1.23).

Results in 2013 (Table 4.22; Appendix 1.24) showed significant difference in farm types ($P < 0.05$) and highly significant ($P < 0.01$) effect with fertilizer application. Highest average grain yields in both farm types were recorded under DAP treatment whereas the lowest values were recorded by the control. Higher gain yield was recorded in 2013 than in 2012. For example; under DAP fertilizer, yield increments of 40% and 135% respectively were recorded on top and bottom farms. Similarly, yield increments of 27% and 112.5% were recorded on plots treated with NPK 15-15-15 on top and bottom farm types, respectively. The observed yield increment in 2013 over that of 2012 was more drastic in the bottom farms than in the top farms. The combined analysis results (Table 4.23; Appendix 1.25) showed the highly significant influence of year by fertilizer treatment interaction of year on millet grain yield (Figure 4.15).

Table 4.21. Effects of fertilizer application, farm type and interaction millet grain yield in 2012

Fertilizer type	Grain yield (kg ha^{-1})	
	Top farm	Bottom farm
Control	451	161
DAP	642	245
NPK151515	703	256
NPK151515+TRP	845	345
χ^2 pr. Fertilizer x Farm type	0.018	
s.e.d. Fertilizer x Farm type	116	

*Treatment means are average of four replicates

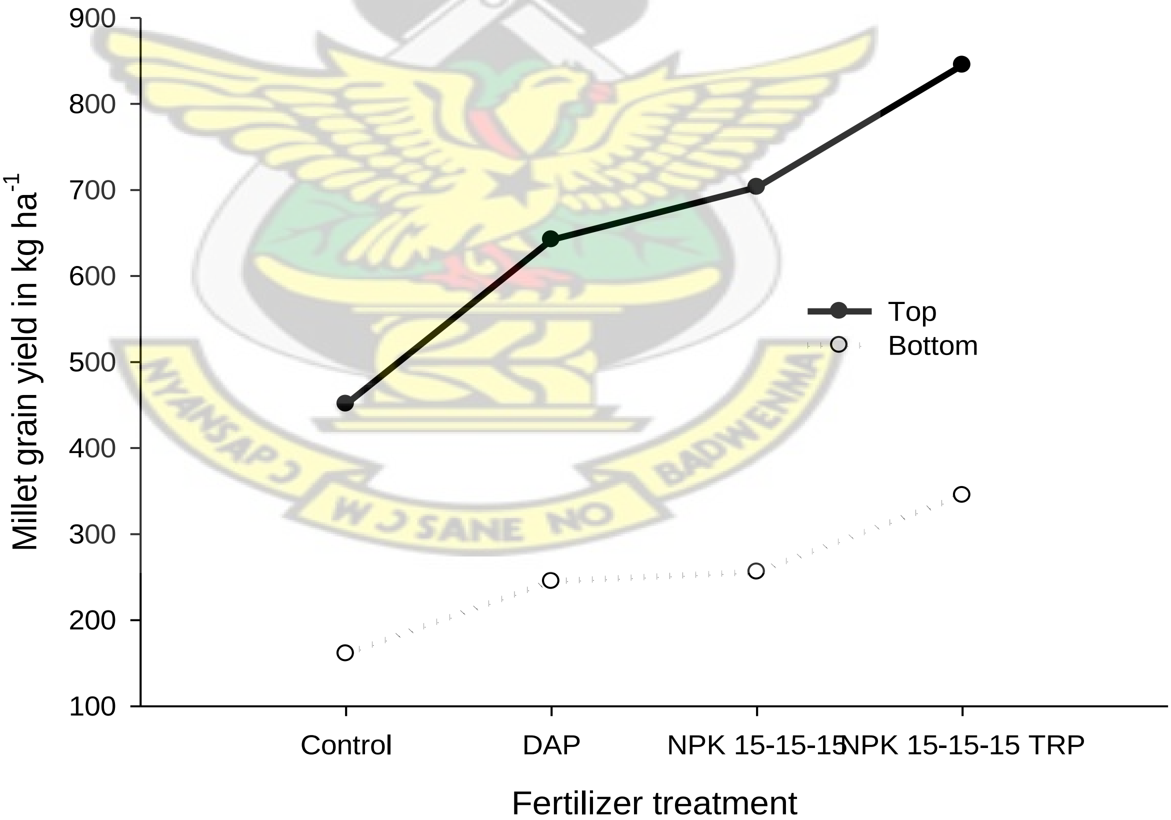

Figure 4.14. Effect of fertilizer treatment x farm type interaction on millet grain yield at Karabédji in 2012

Table 4.22. Effects of fertilizer application, farm type and interaction on grain yield in 2013

Fertilizer type	Grain yield (kg ha^{-1})	
	Top farm	Bottom farm
Control	586	365
DAP	901	576
NPK151515	895	543
NPK151515+TRP	797	487
χ^2 pr. Farm type	0.045	
s.e.d. Farm type	164	
χ^2 pr. Fertilizer	< 0.001	
s.e.d. Fertilizer	76	

*Treatment means are average of four replicates

Table 4.23. Effect of fertilizer application, farm type, year and interactions on grain yield

Fertilizer type	Grain yield (kg ha^{-1})			
	Top farm		Bottom farm	
	2012	2013	2012	2013
Control	451	586	161	365
DAP	642	901	245	576
NPK151515	703	895	256	544
NPK151515+TRP	845	797	345	487
χ^2 pr. Year x Fertilizer	< 0.001			
s.e.d. Year x Fertilizer	119			

*Treatment means are average of four replicates

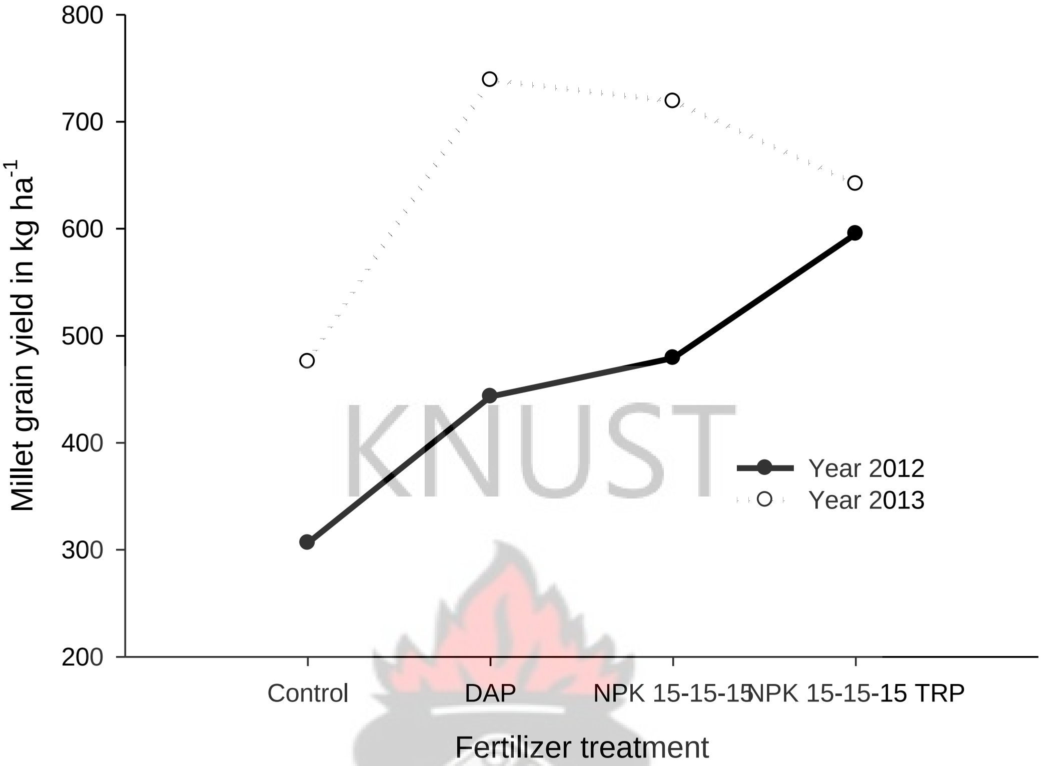

Figure 4.15. Effect of fertilizer treatment x year interaction on millet grain yield at Karabédji

Fertilizer application and year interacted to influence ($P < 0.05$) millet stubble yield (Table 4.24; Appendix 4.26). The trend in variation of stubble yield among fertilizer treatment and farm types was similar to that observed with millet grain yield. On top farm type, highest yields were obtained in NPK 15-15-15 + TRP and DAP treatments while the control recorded the lowest yield in 2012 and 2013. Similar trend was also observed in the bottom farm type. The random factor 'farm by type by year' accounted for 92% of the observed variation in millet stubble yield (Appendix 1.26).

Table 4.24. Effects of fertilizer application, farm type and interactions on millet stubble yield

Fertilizer type	Stubble yield (kg ha^{-1})			
	Top farm		Bottom farm	
	2012	2013	2012	2013
Control	3123	3087	2500	2600
DAP	3967	4587	2960	3375
NPK151515	3967	3450	3210	3000
NPK151515+TRP	4653	3612	3773	2938
χ^2 pr. Fertilizer x Year			0.005	
s.e.d. Fertilizer x Year			298	

*Treatment means are average of four replicates

4.4.1 Relationships between soil physico-chemical properties and millet yield

Significant positive relationships were found between millet grain yield and both physical and chemical soil properties such as stability of aggregate (Figure 4.16 and Figure 4.17), plant available water (Figure 4.18 and Figure 4.19), exchangeable K content (Figure 4.20) and total phosphorus concentration in leaf (Figure 4.21). Highest correlations were obtained between grain yield and total phosphorus concentration (R^2 = 0.69), followed by exchangeable potassium (R^2 = 0.63). Significant ($P < 0.001$) correlation (R^2 = 0.64) was also obtained between millet stubble yield and total phosphorus level in leaf at maturity (Figure 4.22).

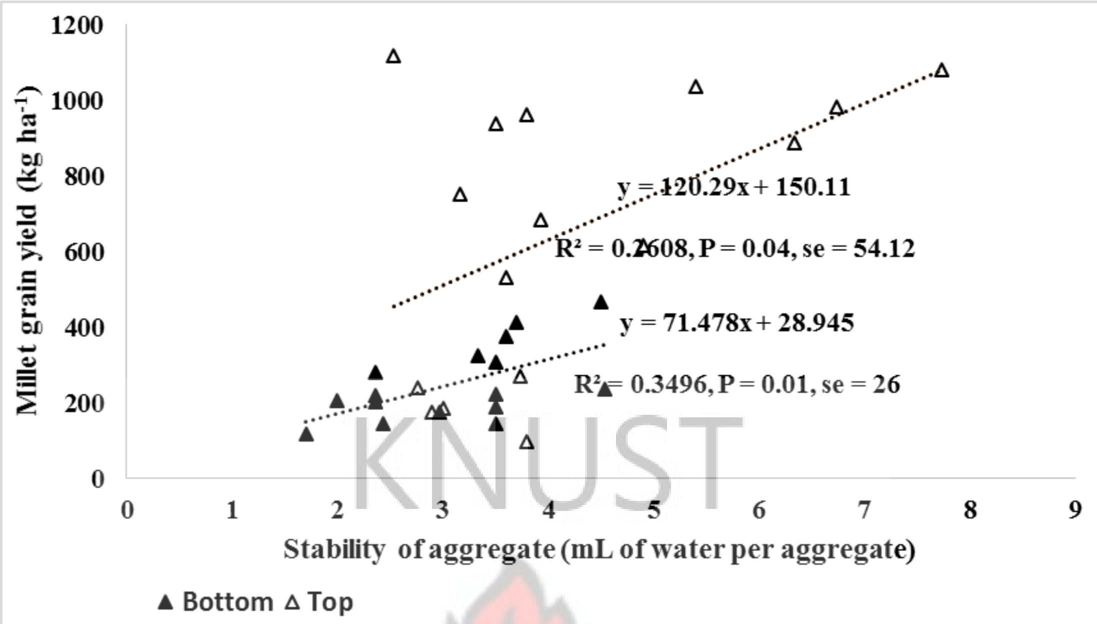

Figure 4.16. Relationship between millet grain yield and stability aggregate by farm type, in 2012

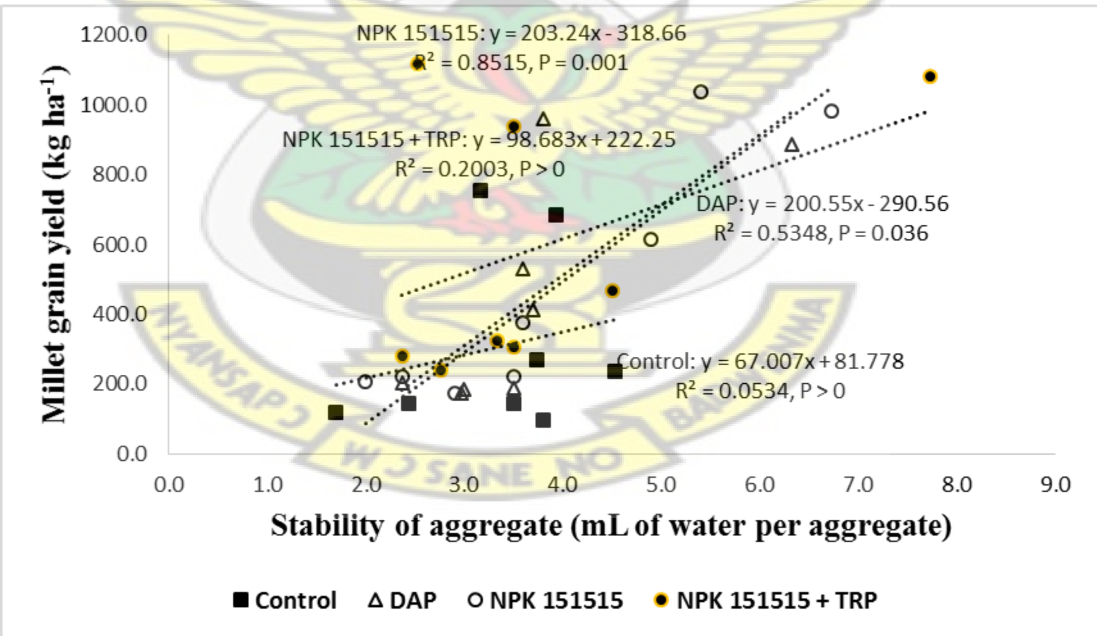

Figure 4.17. Relationship between millet grain yield and stability of aggregate by fertilizer rates

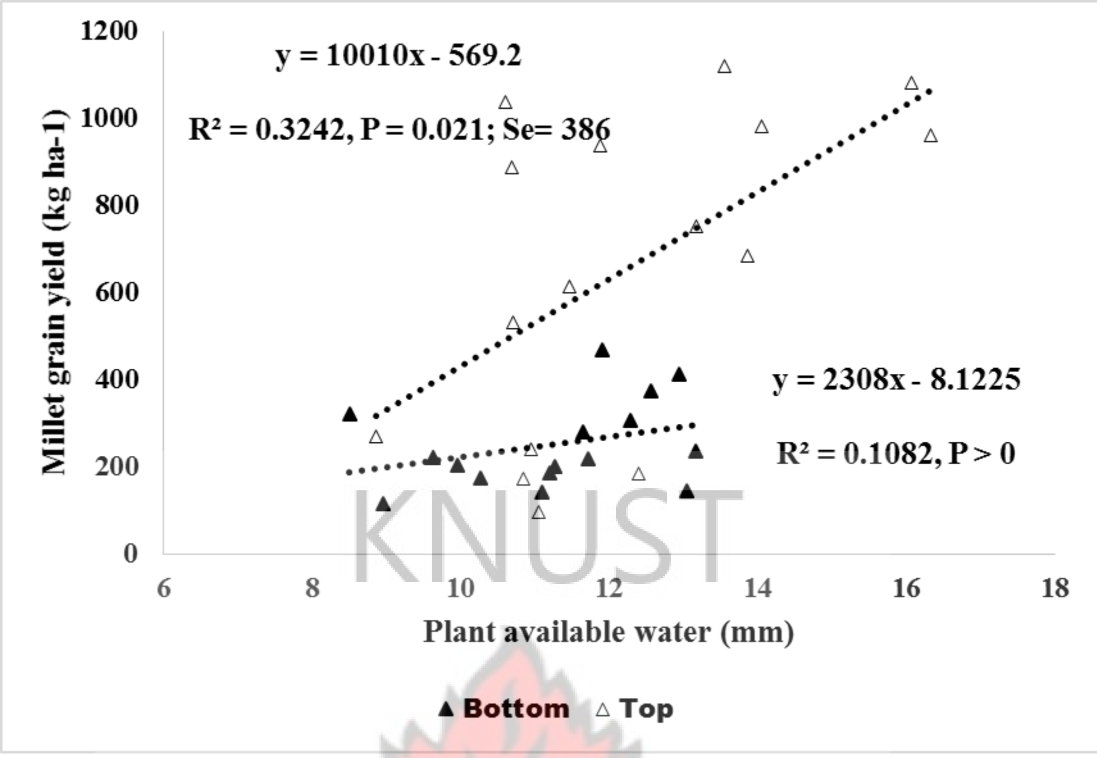

Figure 4.18. Relationship between millet grain yield and plant available water in top and bottom farm types

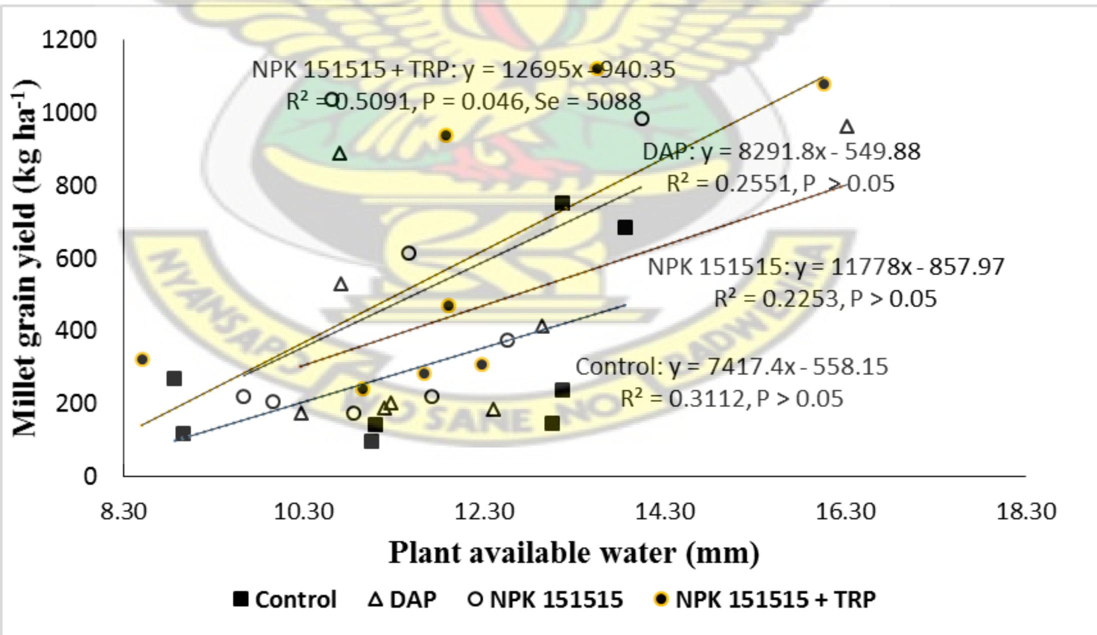

Figure 4.19. Relationship between millet grain yield and plant available water by fertilizer treatment in year 2012

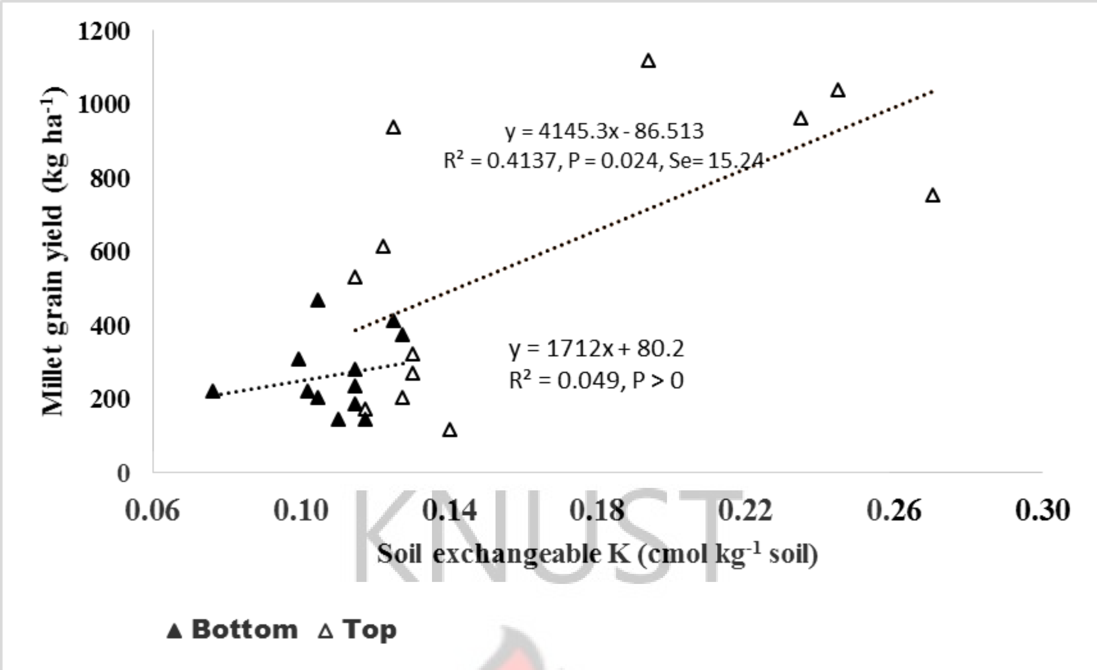

Figure 4.20. Relationship between millet grain yield and exchangeable K

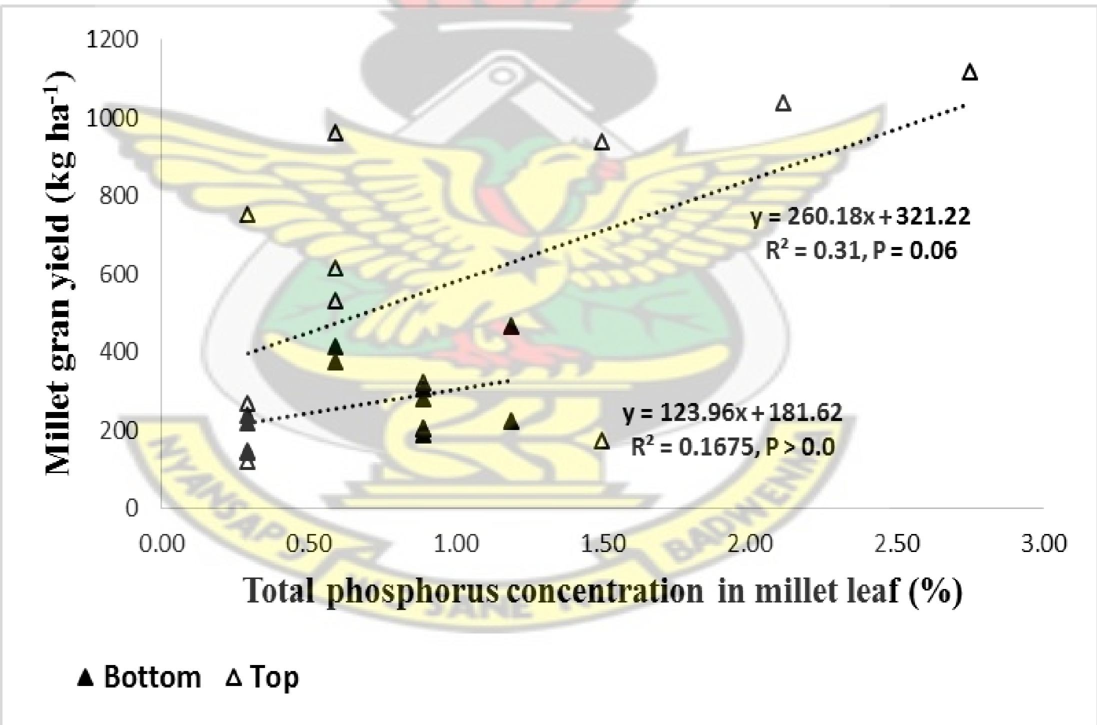

Figure 4.21. Relationship between millet yield and total P concentration in millet leaf in top and bottom farm types

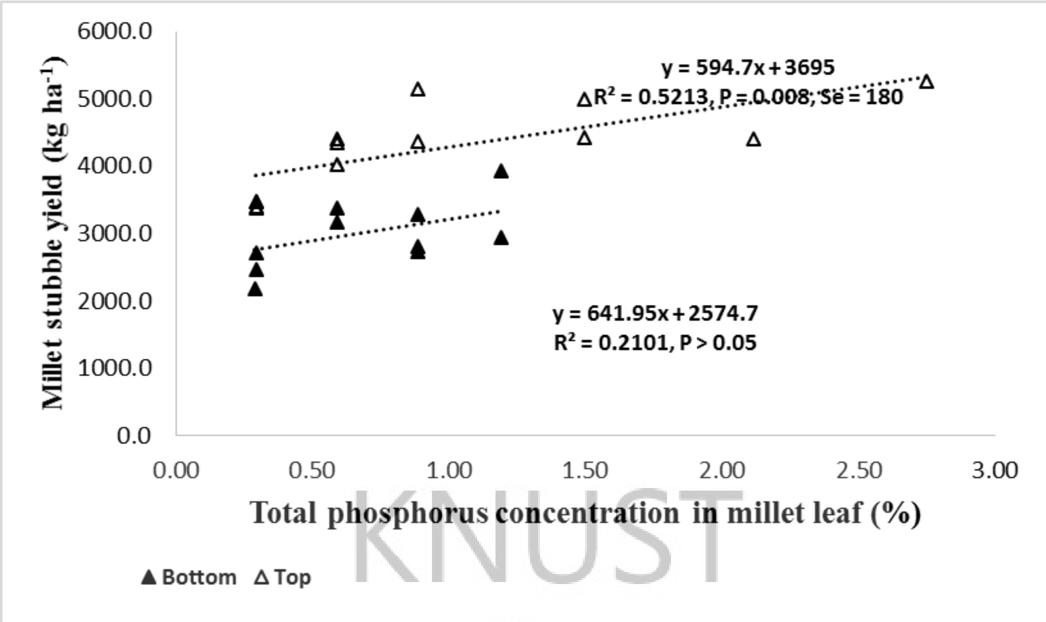

Figure 4.22. Relationship between millet stubble yield and total phosphorus concentration in millet leaf in top and bottom farm types

4.5 Soil properties of fallow sites

Selected soil physical and chemical properties of fallow fields (Appendix 2) showed low organic carbon and N, P and K contents. Particle size analysis showed low clay and silt contents and high proportion sand. Moreover, the high bulk density and low plant available water are characteristics of the Sahelian sandy soil.

4.6 Simulation of millet grain and biomass yields using APSIM

The results of the simulation of millet grain and biomass yields are presented in Tables to ensure readability of model output (Appendix 4).

4.6.1 Predicted and observed millet grain yields

Simulated and measured millet grain yields for the control, DAP, NPK and NPK + TRP (Tahoua Rock Phosphate) treatments in top farm types are presented in Table 4.25. The model-predicted millet grain yields in 2012 were 275 kg ha^{-1}, 941 kg ha^{-1}, 944 kg ha^{-1} and 992 kg ha^{-1} for the control, DAP, NPK 15-15-0 (or NPK) and NPK

15-15-0 + RP (or NPK+ TRP) treatments, respectively whereas the observed values were 441 kg ha^{-1}, 642 kg ha^{-1}, 703 kg ha^{-1} and 845 kg ha^{-1} for the same treatments. In 2013, the predicted value for the control was 159 kg ha^{-1} against 586 kg ha^{-1} observed; for the DAP treatment, predicted yield was 904 kg ha^{-1}, whereas the measured was 901 kg ha^{-1}; for NPK, 894 kg ha^{-1} was predicted against 895 kg ha^{-1} observed; and for the NPK+ RP, 965 kg ha^{-1} was predicted against 797 kg ha^{-1} observed. The model underestimated millet grain yield for the control treatments in both 2012 and 2013 with the top farm type.

For the bottom farm type (Table 4.26), 99 kg ha^{-1} grain yield was predicted against 161 kg ha^{-1} measured in the control treatment in 2012. In 2013, 167 kg ha^{-1} was predicted against 365 kg ha^{-1} observed in the same treatment. The predicted and observed millet grain yields under the DAP treatment were 382 kg ha^{-1} and 245 kg ha^{-1} in 2012. Whilst in 2013, these were 524 kg ha^{-1} and 576 kg ha^{-1} respectively. In 2012 predicted millet grain yield for NPK treatment was 440 kg ha^{-1} versus an observed value of 256 kg ha^{-1} whilst in 2013 these values were 474 kg ha^{-1} and 543 kg ha^{-1}, respectively. Both predicted and observed grain yields for the NPK+ TRP in 2012 and 2013 seasons were comparable (Table 4.26). Generally, the model-predicted values were not far from the observed for millet grain yield in both 2012 and 2013 seasons.

4.6.2 Predicted and observed millet biomass yields

Table 4.27 shows predicted and observed millet biomass yields for the control and the fertilizer treatments in top farm types in year 2012 and 2013. Simulated millet biomass yields in 2012 was 3166 kg ha^{-1} for an observed value of 3123 kg ha^{-1} for the control treatment, however, in 2013 these values were 2060 kg ha^{-1} and 3088 kg ha^{-1}, respectively. Predicted and observed biomass yields for the DAP treatment were

4131 kg ha^{-1} and 3967 kg ha^{-1} in 2012 whereas these values were 3606 kg ha^{-1} and 4587 kg ha^{-1} in 2013. Predicted and observed biomass yields obtained in 2012 and 2013 for both NPK and NPK+ RP treatments of the top farm types were comparable. Except that the model overestimated millet biomass yield with about 17% in the NPK + TRP treatment in 2013 (Table 4.27). In 2013, the predicted biomass value in the control treatment of the top farm type was however underestimated by about 30% by the model.

Simulated and measured millet biomass yields in the bottom farm type (Table 4.28), were 559 and 2500 kg ha^{-1}, respectively for the control treatment in 2012. In 2013 these values were 547 kg ha^{-1} and 2600 kg ha^{-1}, respectively. For the DAP treatment, 1516 kg ha^{-1} was predicted against 2960 kg ha^{-1} observed in 2012, whereas 1559 kg ha^{-1} was predicted against 3375 kg ha^{-1} observed for the same treatment in 2013. Similar underestimation of millet biomass yields were observed in both 2012 and 2013 seasons for the NPK and NPK + RP treatment under bottom farm type. Generally, these predicted biomass yields were 50% lower than the observed values (Table 4.28).

Table 4.25. Predicted and observed millet grain yield for control and fertilizer treatments in top farm types in Karabédji, Niger

Fertilizer type	Year	Millet grain yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	275	441
	2013	159	586
Dap	2012	941	642
	2013	904	901
NPK 15-15-15	2012	944	703
	2013	894	895
NPK 15-15-15 + TRP	2012	992	845
	2013	965	797

Table 4.26. Predicted and observed millet grain yield for control and fertilizer treatments in bottom farm types in Karabédji, Niger

		Millet grain yield (kg ha^{-1})	
Fertilizer type	Year	Predicted	Observed
Control	2012	99	161
	2013	167	365
DAP	2012	382	245
	2013	524	576
NPK 15-15-15	2012	440	256
	2013	474	543
NPK 15-15-15 + TRP	2012	382	345
	2013	524	487

Table 4.27. Predicted and observed millet biomass yield for control and fertilizer treatments in top farm types, Karabédji, Niger

Fertilizer type	Year	Millet biomass yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	3166	3123
	2013	2060	3088
DAP	2012	4132	3967
	2013	3607	4587
NPK 15-15-15	2012	4230	3967
	2013	3563	3450
NPK 15-15-15 + TRP	2012	4861	4653
	2013	4252	3612

Table 4.28. Predicted and observed millet biomass yield for control and fertilizer treatments in bottom farm types, Karabédji, Niger

Fertilizer type	Year	Millet biomass yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	559	2500
	2013	547	2600
DAP	2012	1515	2960
	2013	1557	3375
NPK 15-15-15	2012	1395	3210
	2013	1529	3000
NPK 15-15-15 + TRP	2012	1515	3773
	2013	1557	2937

4.6.3 Simulation of millet grain and biomass yield using generated weather data

Millet grain and biomass yields for the control and fertilizer treatments for both top and bottom farm types using generated weather data are shown in Tables.4.29, 4.30, 4.31 and 4.32. Similar trends in both grain and biomass yields were obtained for both millet grain yield and biomass yield using the generated weather data as when the measured climatic data were used. Millet grain yield was comparable in both treatments and farm type whilst the model underestimated millet biomass yield in bottom farm type both in 2012 and 2013 seasons. This underestimation was more pronounced in the control treatments (Table 4.32).

Table 4.29. Predicted and observed millet grain yields for the control and fertilizer treatments in top farm types using generated climatic data, Karabédji, Niger

Fertilizer type	Year	Millet grain yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	641	441
	2013	540	586
DAP	2012	916	642
	2013	855	901
NPK 15-15-15	2012	952	703
	2013	873	895
NPK 15-15-15 + TRP	2012	976	845
	2013	870	797

Table 4.30. Predicted and observed millet grain yields for the control and DAP treatments in bottom farm types using generated climatic data, Karabédji, Niger

Fertilizer type	Year	Millet grain yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	137	161
	2013	178	365
DAP	2012	471	245
	2013	545	576
NPK 15-15-15	2012	587	256
	2013	538	543
NPK 15-15-15 + TRP	2012	471	345
	2013	545	487

Table 4.31. Predicted and observed millet biomass yield of the control and fertilizer treatments in top farm types using generated climatic data, Karabédji, Niger

Fertilizer type	Year	Millet biomass yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	2387	3123
	2013	1632	3088
DAP	2012	4042	3967
	2013	3531	4587
NPK 15-15-15	2012	4340	3967
	2013	3505	3450
NPK 15-15-15 + TRP	2012	4860	4653
	2013	4070	3612

Table 4.32. Predicted and observed millet biomass yield of the control and fertilizer treatments in bottom farm types using generated climatic data, Karabédji, Niger

Fertilizer type	Year	Millet biomass yield (kg ha^{-1})	
		Predicted	Observed
Control	2012	665	2500
	2013	515	2600
DAP	2012	1877	2960
	2013	1420	3375
NPK 15-15-15	2012	1845	3210
	2013	1499	3000
NPK 15-15-15 + TRP	2012	1877	3773
	2013	1420	2937

4.6.4 Model evaluation

RMSE and d index of difference of millet grain and biomass yields using measured and generated weather conditions are shown in Table 4.33. The model simulated well the observed grain yield which is illustrated by the low RMSE of 179 kg ha^{-1} and the high d index of 0.88 when the measured weather data was used. Both RMSE and d index for grain yield were also good for the generated weather data. Simulated biomass yield using measured weather data resulted in RMSE and d index values in the order of 1333 kg ha^{-1} and 0.62, respectively. Similar results were obtained with the generated weather data. Furthermore, significant ($P < 0.01$; $R^2 = 0.68$) and positive relationship was obtained (Figs. 4.23 and 4.24) between predicted and measured millet grain and biomass yields ($P < 0.01$; $R^2 = 0.65$).

The results of simulations using measured weather data for the nearest meteorological station were comparable to that of the generated weather data of the study site for both biomass and grain yields (Figs 4.25 and 4.26). This is also illustrated by the high correlation coefficients obtained when testing the degree of relationship between the procedures using measured and generated data on biomass and grain yield of millet (Figs 4.27 and 4.28).

Table 4.33. Performance of APSIM in simulating millet grain and biomass yields using measured and generated weather data

Type of climatic data	Millet yield	Statistics	Values
Measured	Grain	RMSE	179
		d	0.88
	Biomass	RMSE	1333
		d	0.62
Generated	Grain	RMSE	162
		d	0.88
	Biomass	RMSE	1296
		d	0.63

* RMSE and d are expected to be as close as possible to 0 and 1 respectively

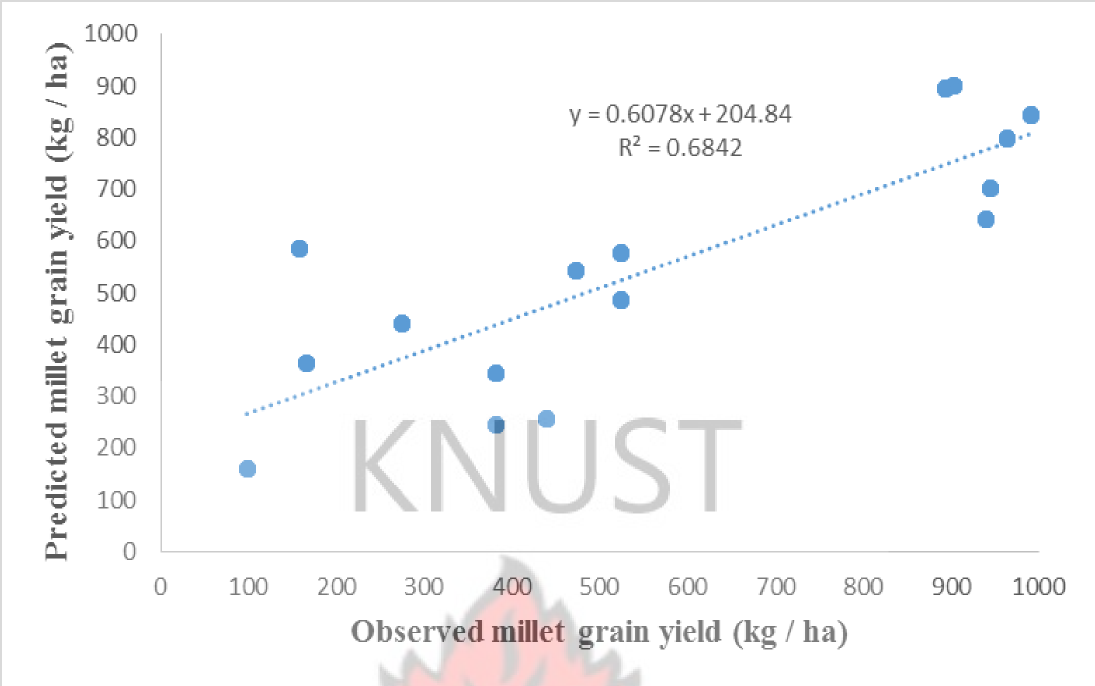

Figure 4.23. Relationship between APSIM-predicted and measured millet grain yield for the control and fertilizer treatments in two farm types (measured weather data)

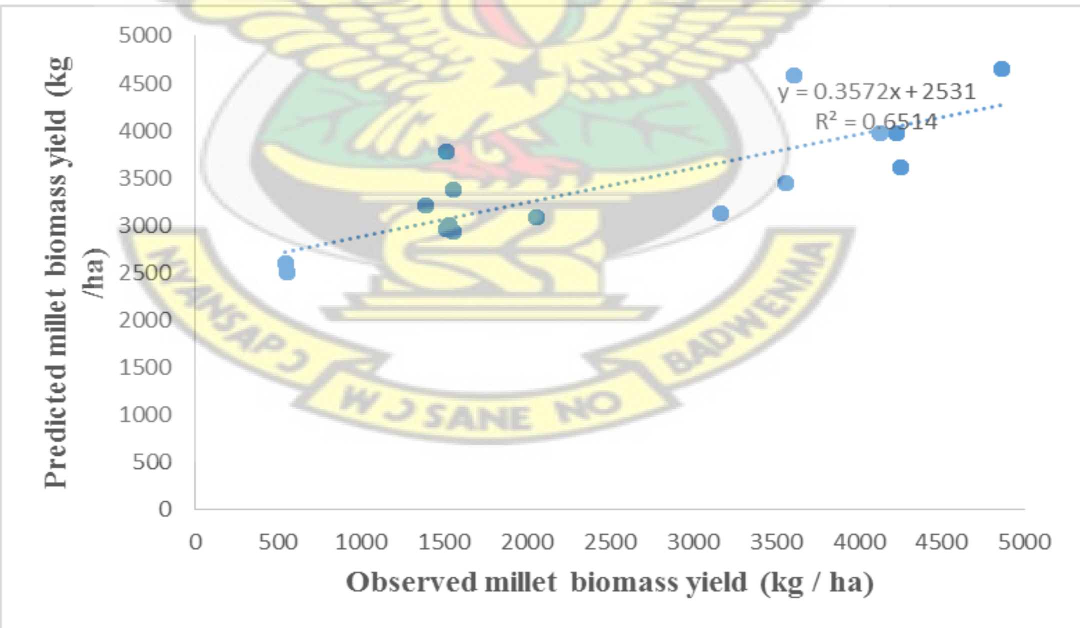

Figure 4.24. Relationship between APSIM-predicted and measured millet biomass yield for the control and fertilizer treatments in two farm types (measured weather data)

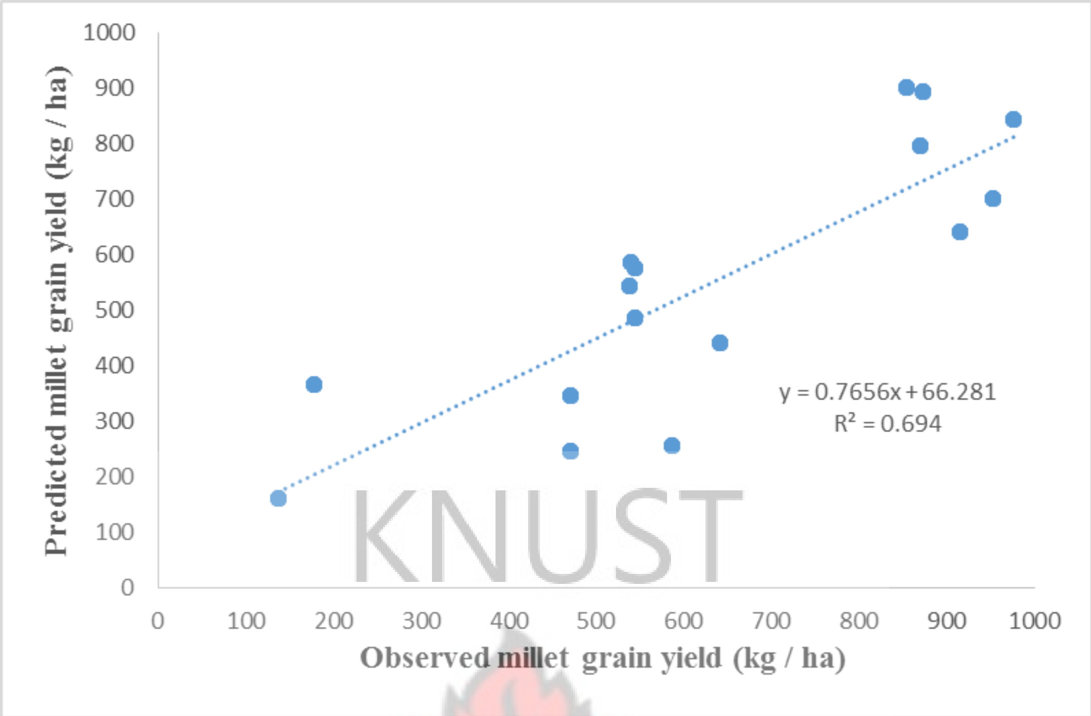

Figure 4.25. Relationship between APSIM-predicted and measured millet grain yield for the control and fertilizer treatments in two farm types (generated weather data)

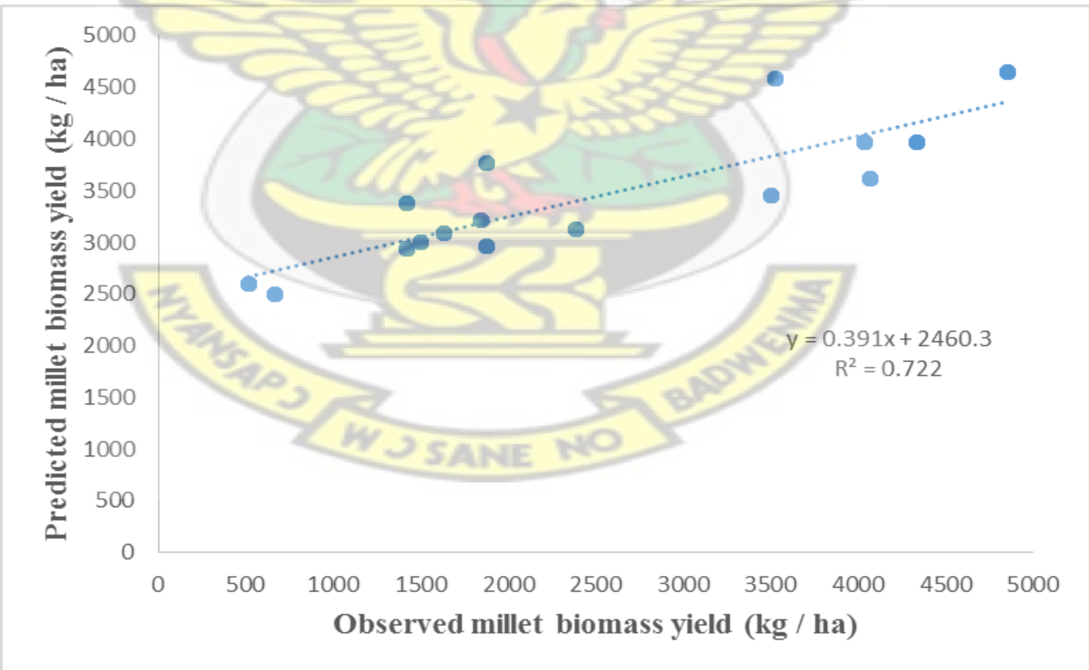

Figure 4.26. Relationship between APSIM-predicted and measured millet biomass yield for the control and fertilizer treatments in two farm types (generated weather data)

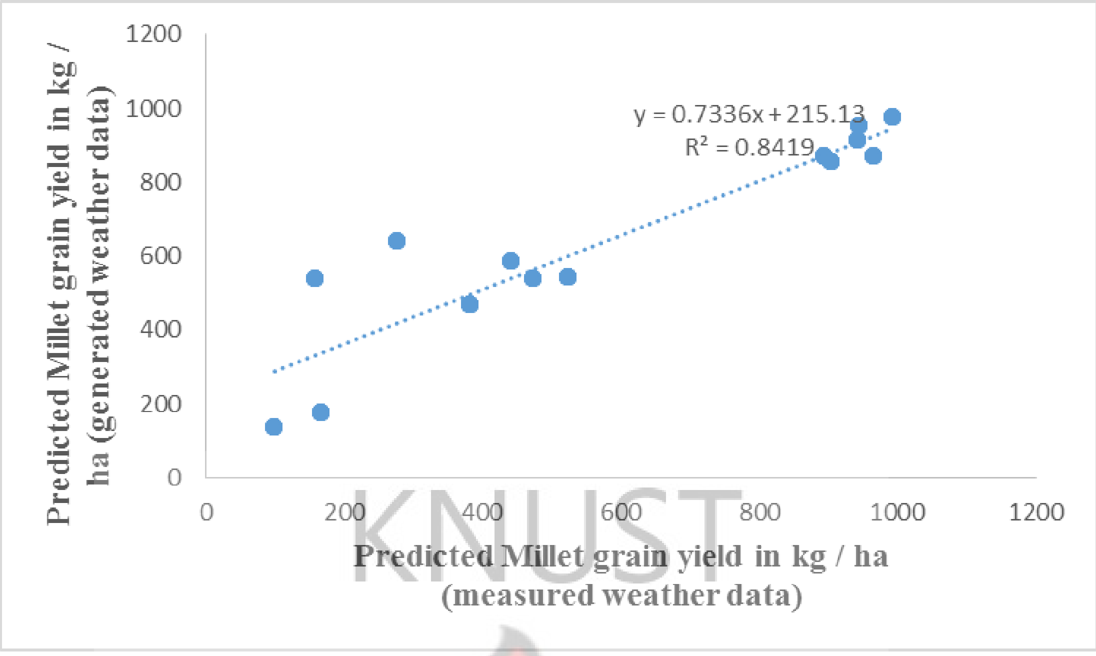

Figure 4.27. Relationship between APSIM-predicted millet grain yield for the control and fertilizer treatments in two farm types using measured climatic data and biomass yield predicted using generated weather data

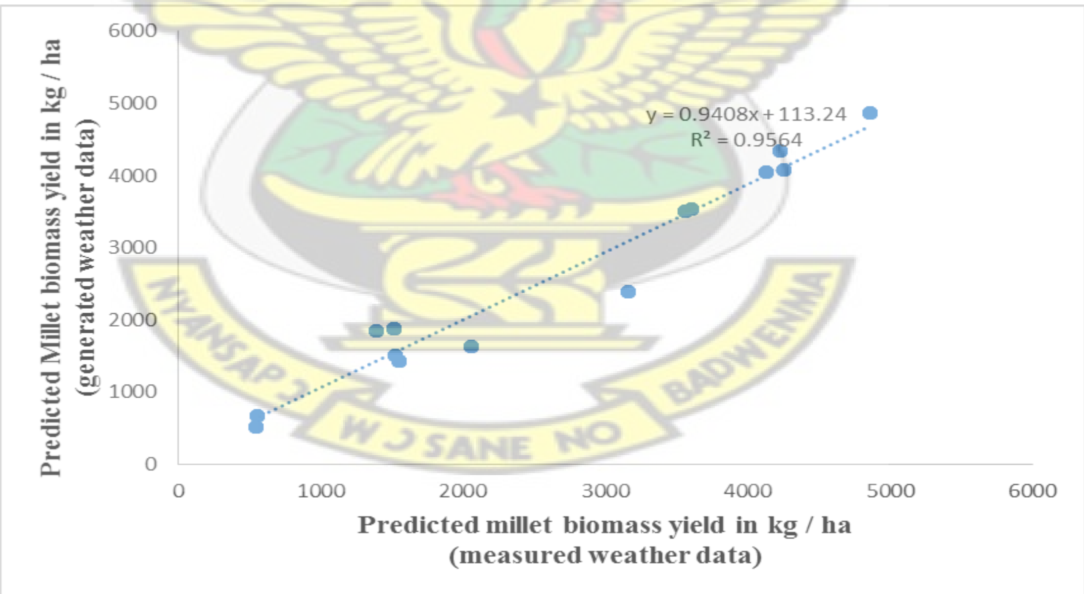

Figure 4.28. Relationship between APSIM-predicted millet biomass yield for the control and fertilizer treatments in two farm types using measured climatic data and biomass yield predicted using generated weather data

4.7 Socio-economic survey

To show variation in soil management practices among farmers, farmers who participated in the on-farm evaluation of soil fertility management trial (or participants) were compared to those who did not participate (non-participants).

4.7.1 Individual and household characteristics at the survey site

Results on individual and household characteristics (Table 4.34) indicated that 29% of farmers engaged in the on-farm evaluation of soil fertility management technology (or participants) and 43% of farmers not engaged (non-participants) did not attend formal school. However, an important proportion of the respondents: both non-participant and participant (39 and 52% respectively) farmers have undergone Koranic studies. Most of the respondents have between 6 and 10 dependents with only less than 20% having between 1 to 5 dependents. Fifty percent of non-participants farmers and 69% of participants are members of Farmer-Based Organizations (FBOs).

Table 4.34. Individual and household characteristics

Variable	Description	Farmer characteristics	
		Non-participant	Participant
Educational Level	No formal education	36 (42.9)	5 (29.4)
	Primary	4 (4.8)	1 (5.9)
	Secondary	2 (2.4)	1 (5.9)
	Koranic	33 (39.3)	9 (52.9)
	Adult literate	5 (6.0)	1 (5.9)
	Koranic and primary	3 (3.6)	0 (0.0)
	Koranic and Adult Literate	1 (1.2)	0 (0.0)
	Count	84 (100.0)	17 (100.0)
Dependency	1-5	16 (19.0)	1 (5.9)
	6-10	48 (57.1)	7 (41.2)
	11-15	16 (19.0)	4 (23.5)
	> 15	4 (4.8)	5 (29.4)
	Count	84 (100.0)	17.0 (100.0)
FBO	Yes	46 (54.8)	11 (68.8)
	No	38 (45.2)	5 (31.3)
	Count	84 (100.0)	16 (100.0)

Values in parenthesis are percentages

4.7.2 Farmer typology and soil fertility management practices

Eight groups of farmers were identified based on three main criteria: farmer's participation (in on-farm evaluation of soil fertility demonstration or project activities); farmer's FBO membership status, and farmer's resource endowment status. Soil fertility management varied among the 8 groups of farmers (Figure 4.29 and 4.30). Average quantity of fertilizer used among farmers groups varied between 3 and 14 kg ha^{-1} mainly from three main sources namely NPK, DAP and urea fertilizer. The highest average quantity of fertilizer used was generally recorded in farmers members of demonstration activities (demos) and farmer-based organisation (FBO) but not among the endowed group. Demo, FBO and endowed group recorded the highest farm income. Farm income was found to be more related to labour availability and resource endowment. For manure cost, the best performance was noticed with endowed farmers who neither attend FBO nor demos activities whereas the lowest performance was by the demonstration farmers that are not endowed and not FBO members (Figure 4.30). Generally, for both members and non-members of demonstration, endowed farmers apply more farm inputs than the non-endowed farmers and farm income is more related to resource endowment. Resource endowed farmers who participate in demonstration and FBO activities have best performance. However, non-endowed farmers who participated in demos and FBO activities were found to apply fertilizer yet had the lowest farm income.

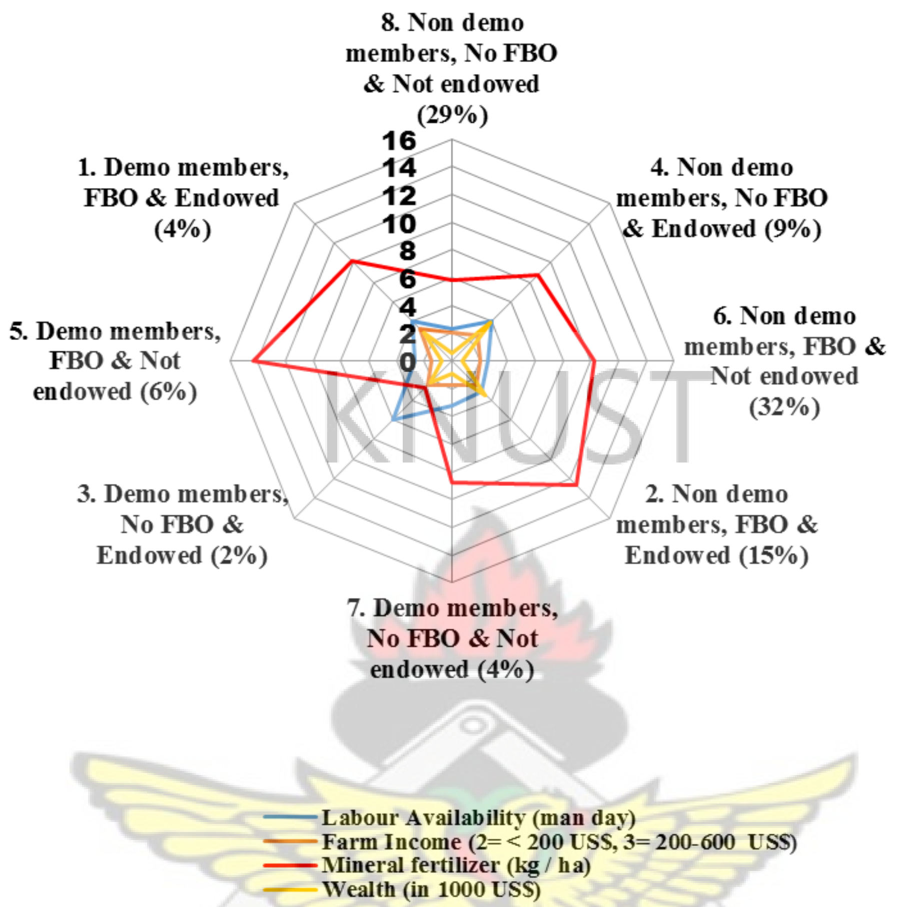

Figure 4.29. Mean quantity of mineral fertilizer used, labour availability and farm income of different groups of farmers

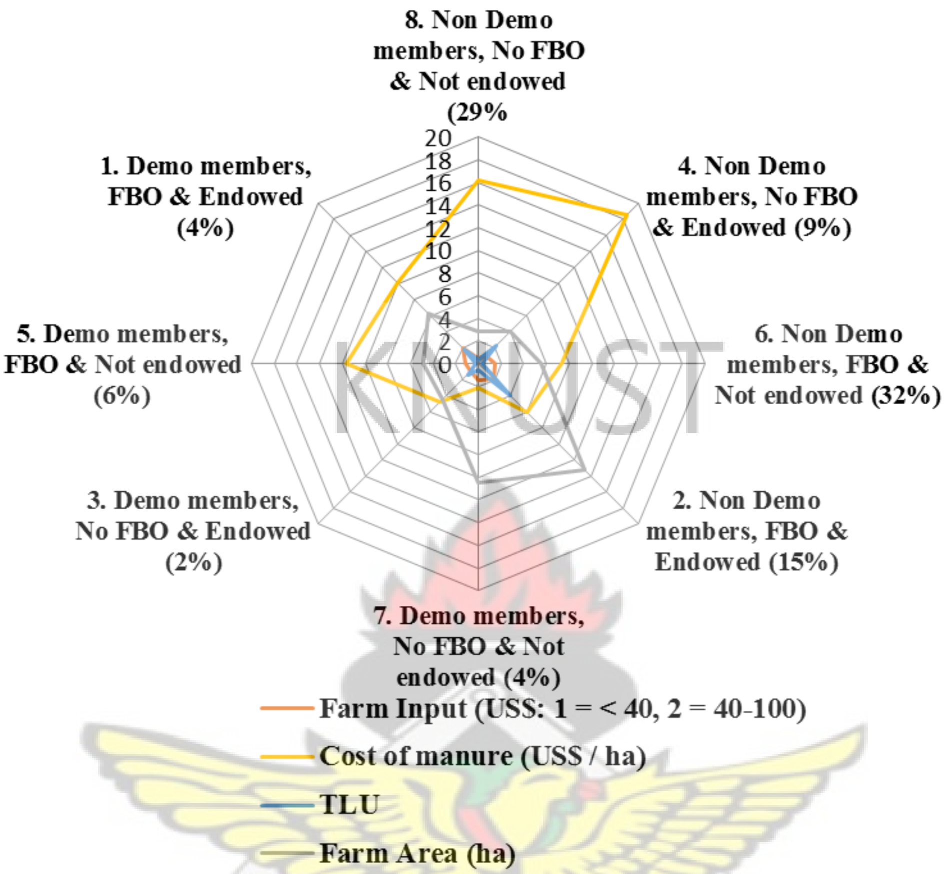

Figure 4.30. Average cost of household manure, farm input and TLU of different groups of farmers

The yearly expenditure on farm inputs is also shown in Table 4.35. 71% of non-participant farmers applied less than US$ 100 worth inputs whereas this category include 44% of participant farmers. It was also found that only 20% of non-participant farmers purchase US$ 100-200 of farm inputs compared to 44% of participant farmers. About 10% of farmers were in the highest class of input use > US$ 200.

Table 4.35. Input use intensity among demo and non-demo participants

Variable	Farm input class*	Number of farmers per class	
		Non-participant	Participant
Cost of input	< 40	20 (25)	3 (18.8)
	40-99	37 (46.3)	4 (25.0)
	100-199	16 (20.0)	7 (43.8)
	>200	7 (8.8)	2 (12.5)

*Figures in parenthesis are percentages of respondents; Classes are in US$ (1 US$ = Cfa 500)

4.7.3 Constraints and opportunities related to farming practices

Results (Table 4.36) on farmers' reasons for their low use of inorganic fertilizer showed that most farmers in the area attributed it to lack of credit facility to purchase the input as reported earlier by Njeunga *et al*. (2005). A lower percentage of farmers sharing the same point of view was noticed in the demonstration village (or project) as compared to non-demo villages (non-project). Moreover, fertilizer availability was viewed as less important by farmers in both project and non-project villages than the lack of credit facility. Decline in rainfall and decrease in soil fertility were viewed as most threatening factors to crop production by most farmers (Table 4.37). Among the main opportunities from which farmers could benefit most were input shops, followed by project and FBO in the project village, whereas, in non-project villages, these were project followed by municipality (Table 4.34).

Table 4.36. Farmers' reasons for inadequate use of inorganic fertilizer, Karabédji

Constraint	Reasons*	Non project site	Project site	Total
Inadequate use of mineral fertilizer use	Lack of credit facility	55 (93.2)	27 (67.5)	82 (82.8)
	Unavailability of fertilizer	3 (5.1)	0 (0.0)	3 (3.0)
	Lack of credit facility and unavailability of fertilizer	1 (1.7)	13 (32.5)	14 (14.1)
Total		59 (100.0)	40 (100.0)	99 (100.0)

*Figures in parenthesis are percentages of respondents

Table 4.37. Farmer's perceptions about food security-related constraints

Which among the following affects you most?	Non-project site*	Project site	Total
Decline in rainfall	32 (55.2)	12 (31.6)	(44) 45.8
Soil fertility decline	13 (22.4)	11 (28.9)	24 (25.0)
Farm fragmentation	2 (3.4)	0 (0.0)	2 (2.1)
Increased in population	1 (1.7)	0 (0.0)	1 (1.0)
Decline in rainfall & Soil fertilizer	9 (15.5)	15 (39.5)	24 (25.0)
Decline in rainfall & Farm fragmentation	1 (1.7)	0 (0)	1 (1.0)
Total	58 (100.0)	38 (100.0)	96 (100.0)

*Figures in parenthesis are percentages of respondents

Table 4.38. Farmers' views about opportunities they benefit most from in their farming activities

Opportunities*	Non project site	Project site	Total
Presence of project	10 (23.3)	5 (12.8)	15 (18.3)
Municipality	1 (2.3)	0 (0)	1 (1.2)
Farmer Association	0 (0)	5 (12.8)	5 (6.1)
Input Shop	0 (0)	18 (46.2)	18 (22)
Warrantage system	14 (32.6)	0 (0)	14 (14)
Presence of project & Municipality	8 (18.6)	0 (0)	8 (9.8)
Presence of project & Input shop	3 (7.0)	4 (10.3)	7 (8.5)
Presence of project & Warrantage system	1 (2.3)	0 (0)	1 (1.2)
Municipality & input shop	1 (2.3)	0 (0)	1 (1.2)
Municipality & Warrantage system	2 (4.7)	0 (0)	2 (2.4)
Farmer's association & input shop	0 (0)	3 (7.7)	3 (3.7)
Input shop & Warrantage system	0 (0)	1 (2.6)	1 (1.2)
Presence of project, Municip. & Farmer association	0 (0)	1 (2.6)	1 (1.2)
Presence of project, Municip. & Input shop	3 (7.0)	1 (2.6)	4 (4.9)
Presence of project, Farmer assoc. & input shop	0 (0)	1 (2.6)	1 (1.2)
Total	43 (100.0)	39 (100.0)	82 (100.0)

*Values in parentheses are percentages

Additionally, test of independence of mean of farm income did not differ significantly between participant and non-participant farmers (Table 4.39). However, the number of participant farmers applying chemical fertilizer, manure and mulch was consistently higher than non-participant (Table 4.40). Moreover, mean difference analysis showed significantly higher average quantities of chemical fertilizer and organic manure were observed with participating farmers than non-participants (Table 4.41).

Table 4.39. Test of independence of percentage of farmers by farm income class

Variable	Farm input class*	Non-participant	Participant	χ^2 pr.	P-value
Farm income	< 200	14 (16.9)	5 (29.4)	2.13	0.54
	200-599	49 (59.0)	7 (41.2)		
	600-1,000	12 (14.5)	3 (17.6)		
	> 1,000	8 (9.6)	2 (11.8)		

Percentages are in parenthesis; classes are in US$ (1 US$ = 500 Cfa)

Table 4.40. Soil fertility management and adoption of soil conservation practices among respondents

Variable	Response	Non-participant	Participant
Apply chemical fertilizer	Yes	58 (69.9)	13 (81.2)
	No	25 (30.1)	3 (18.8)
Count		83 (100.0)	16 (100.0)
Apply organic manure	Yes	56 (96.6)	16 (100.0)
	No	2 (3.4)	0 (0.0)
Count		58 (100.0)	16 (100.0)
Mulch	Yes	9 (11.4)	2 (12.5)
	No	70 (88.6)	14 (87.5)
Count		79 (100.0)	16 (100.0)
Half moon	Yes	2 (2.5)	0 (0.0)
	No	77 (97.5)	16 (100.0)
Count		79 (100.0)	16 (100.0)
Zai	Yes	10 (12.7)	0 (0.0)
	No	69 (87.3)	16 (100.0)
Count		79 (100.0)	16 (100.0)

Percentages are in parenthesis

Table 4.41. Average quantity of farm inputs used, TLU and farm area distribution among survey respondents

Variable	Description	Non-participant		Participant		Mean Diff.
		Mean	SD	Mean	SD	
Area	Area under cultivation (ha)	6.38	10.29	6.32	6.05	-0.60
TLU	Tropical livestock unit	1.2	2.97	0.83	0.85	0.37
QPA	Rate of inorganic fertilizer applied ($kg.ha^{-1}$)	7.24	8.94	12.11	10.80	4.86*
Carts number	No. of household manure carts transported per year	32.66	21.89	49.15	37.71	16.55**

**and * respectively denote significance at 5 and 10%

CHAPTER FIVE

5.0 DISCUSSION

5.1 Soil physical and hydrologic properties

5.1.1 Soil particle size distribution

The particle size distribution of the soil at the study site is characteristic of the coarse Arenosols that occupy most of the millet growing areas in Niger. The proportion of different particle sizes observed in both top and bottom farm types are similar to those of coarse sandy soil in the area reported previously on the same type of soil (Payne *et al*., 1991; Zaongo *et al*., 1994, Gandah *et al.*, 2003).

5.1.2 Effect of fertilizer application, farm type and interactions on soil specific volume

The observed values of soil specific volume were low indicating high bulk density which is a characteristic of the Sahelian Arenosols. Fechter *et al*. (1991), Payne *et al*. (1991) and Gandah *et al.* (2003) also reported similar values. Soil specific volume is inversely related to soil bulk density - the higher the bulk density, the lower the specific volume. Soil specific volume is a measure of soil compaction and the ranges of soil specific volume observed in this study are within the optimal values. Specific volume ranging from 1.11 to 0.80 were proposed for maximal field crop production in fine to medium-structured soils (Reynold, 2009). However, there was no effect of fertilizer application application and farm type on soil specific volume. The lack of significant effect of long-term soil fertility management practices on soil bulk density has been reported (Lal, 1997; Dunjana *et al*., 2012). Moreover, the difference in farm by type did not play a major role in the observed variability in soil specific volume between the treatments as the random term 'farm by farm type' accounted only for 11% of the variance.

5.1.3 Effect of fertilizer application, farm type and interactions on air capacity

The range of air capacity values observed is characteristic of well-drained sandy soil. Air capacity is an indication of soil aeration. For fine textured soils to compensate for respirative demands of biological activity and low gas diffusion rate a minimum of 0.15 m^3 m^{-3} of air capacity is required (Reynold *et al.*, 2007). The smallest value observed in this study was 0.171 m^3 m^{-3} as the soil is coarse textured with no problem of soil aeration.

5.1.4 Effect of fertilizer application, farm type and interactions on soil water content at field capacity and on relative water capacity

The amount of water retained at field capacity did not vary significantly under the different fertilizer treatments and farm types. The observed dispersive values could be attributed to the observed high on-farm variability of properties of the Sahelian sandy soils as previously reported by several authors (Scott-Wendt *et al.,* 1988a; 1988b; Voortman *et al.*, 2003; Voortman *et al.*, 2004; Manyame, 2006).

Similar trend was also observed for the relative field capacity. Amended plots were expected to have significantly higher water content retained at field capacity than the control, which could have influenced the relative water capacity. Soil relative water capacity is the ability of the soil to store water and air relative to its total pore volume (Reynolds, 2007). The expected higher water content could result from increase in organic matter content provided through root biomass accumulation over the years in amended plots than the unamended control. Similar expectations were also made between top and bottom farms. Top farms produced higher biomass and consequently more crop residue is being retained as compared to the bottom farm type.

5.1.5 Effect of fertilizer application, farm types and interactions on soil macro-porosity

Soil macro-porosity define the volume of macro-pores important for microbial activities and plant root development. The low effect of fertilizer application and farm type generally observed on soil macro-porosity and this could be due to the coarse nature of the Sahelian sandy soil characterized by low organic matter and clay contents. High values of macro-porosity is an indication of the presence of macro pores which give to soil its ability to drain excess water and facilitate root proliferation. Macro-porosity values ranging from 0.05-0.10 m^3 m^{-3} were reported to be optimal, whereas values < 0.004 m^3 m^{-3} were reported for degraded soils (Drewry and Paton, 2005; Reynolds, 2009). The decrease in soil macro-porosity with fertilizer by depth interaction observed under the SWRC method could be as a result of weeding operations which aerated the upper soil layer.

It is important to note that the mean values of soil macro-porosity obtained using the SWRC curve and disc infiltrometer method are similar, though no significant changes in macro-porosity were obtained between mean treatments.

5.1.6 Effect of fertilizer application farm types on field-saturated hydraulic conductivity (K_{fs}) and soil sorptivity

The field-saturated hydraulic conductivity was not influenced by the treatment as expected as none of the farms exhibited signs of crusting or shallow rooting depth which could have interfered with infiltration. However, high variability of field-saturated hydraulic conductivity was observed as reported by Reynolds *et al*. (2000) and Sanjit and Shukla (2012). Generally, very low values of K_{fs} were observed which seems unrealistic due to high permeability conditions on such Sahelian Arenosols. Klaij and Vauchaud (1992) measured drainage below millet rooting depth and estimated it at 47% for non-fertilized millet and 33% for field with a higher level of fertilization on the same soil type and in the same area.

The tension infiltrometer seems to have underestimated the field-saturated hydraulic conductivity.

The observed soil sorptivity varied only between matric suctions but did not show any significant change between the fertilizer treatments and farm types. Moroke *et al*. (2009) could not find significant difference in sorptivity between different tillage systems but the parameter was found to be significantly higher in sandy compared to sandy loam soils. Sorptivity is the soil's ability to absorb water under capillary forces thereby indicating the pore volume filled with water at the early stage of infiltration. According to Shaver *et al*. (2013), management practices that can improve soil physical properties such as aggregate stability, bulk density and porosity can indirectly affect sorptivity. The decrease in sorptivity values with increased matric suction was an indication of the influence of antecedent water content as reported by Amer (2012). The lack of significant effect of amendment could be attributed to the low organic matter and clay contents of the Sahelian sandy soil.

5.1.7 Effect of fertilizer application, farm types and interactions on soil structural stability of sandy soil

Soil structural stability showed high sensitivity to the treatments under the water drop method. The observed significant effect of fertilizer application by farm type interaction suggests that the effect of the fertilizer application on the stability of aggregate depends on the type of farm. As expected, the control treatment recorded low values thereby showing the ease at which aggregates could be disintegrated under the control treatment by rain drop impacts. This low structural condition could, facilitate not only leaching of nutrients and clay-sized particles, and or their export through runoff water, but adversely affect soil water holding capacity and ultimately crop growth. Similar report (Diallo *et al*., 2004) showed changes in aggregate stability of an Alfisol, Vertisol and Lithisol under conventional and minimum tillage practices. The authors emphasized positive effect of farming practices that promote the stability of the top soil structure on the susceptibility of soil to erosion. The higher mean values in top fertilized plots than in the control and in the top farm, observed in this study, than in the bottom type farm type could be an indication of increased cohesion between soil particles. The highest structural stability was obtained in the amended treatments of the top farm type.

5.1.8 Effect of fertilizer application, farm types and interactions on Dexter soil physical quality index "S"

Soil physical quality index "S" is a measure of soil microstructure that controls many key soil physical properties (Dexter, 2004). The observed values were within the range of typical "S" values for sandy soils (Dexter, 2004). The Dexter (2004) critical values are: $S \geq 0.05$ (very good physical quality), $0.035 \leq S < 0.050$ (good physical quality), and $S < 0.035$ (poor physical quality). Therefore all observed values in the 10 to 20 cm depth from both top and bottom farm types are within the poor physical quality range. The decrease of "S" with depth could be an indication of decrease in soil physical quality though neither specific volume nor soil organic carbon content did show any significant decrease with the assessed depths. These parameters have been reported to have great effect on "S" (Dexter, 2004). Nonetheless, significant and positive relationship ($P < 0.05$, R^2=0.24) between stability of aggregate and soil physical quality index (Figure 4.6) was obtained.

5.1.9 Effect of fertilizer application, farm type and interactions on plant available water

Plant available water content was sensitive to the combined action of farm type, fertilizer treatment and soil depth (Table 4.11, P = 0.057). The fact that no clear effect of fertilizer was noticed, as no rate consistently recorded higher plant available water over the control treatment, suggests that the relatively higher organic carbon content (Table 4.14) in the top farm than in the bottom farm type had played a role. The relatively higher organic matter content observed in top farm and in fertilized plots might have had positive impact on soil structural stability which, in turn, resulted in higher plant available water. Similar report (Manyame, 2006) showed no significant influence of fertilizer micro-dosing on water balance on a Sahelian sandy soil at Banizoumbou and Bagoua, Niger. Crop residues, organic manure and mineral fertilizer application and corralling are common management practices used to improve soil organic matter status among farmers. However, farmers differ substantially in their ability to increase and maintain the fertility status of their farms. Soil water content has been reported to be among the most sensitive parameters to crop residue removal (Blanco-Canqui and Lal, 2009). Higher plant available water was observed in the long-term fallow (Appendix 2) than the in cultivated fields which is as a result of higher organic carbon content accumulated through increased root biomass and biological activity.

5.2.1 Effects of fertilizer application and farm types on soil chemical properties

The changes in soil pH with time of sampling i.e. before and after the growing season and the relatively lower pH on bottom farms compared to top farm type could be attributed to differences in soil fertility management practices. Addition of household manure and crop residues (left on the field after the previous season) are common practices among farmers, especially with the top farm type. Increase in soil pH was attributed to higher exchangeable cations, particularly K, contained in organic manure than in no manure management (Suzuki *et al*., 2014; Gandah *et al*., 2003).

The observed soil organic carbon in all the treatments was generally very low (< 0.2%). Values reported earlier (IFDC, 2002; Fofana *et al*., 2008) were 0.15% and 0.16% on outfields and infields of Karabédji, respectively. Low organic carbon status of most sub-Saharan African soils is as a result of low carbon sequestration due to low carbon inputs, and to the microbes and termite-induced rapid turnover (Bationo and Buerkert, 2001).

The relatively higher value of OC content observed on top farms compared to bottom type is as a result of differences in the ability of farmers to manage their farms. Soil organic matter content on top farms might have increased through root biomass accumulation as a result of higher management level. Farmers' soil fertility management varies due to differences in socio-economic conditions. Consequently, this reflects on their farms as farmers live in intimacy with their lands. Commonly used practices to improve soil organic matter content by farmers are the application organic manure and retention of crop residues after harvest. Practices that enable regular addition of manure and in small amount: viz corralling (Gandah *et al.*, 2003; Manyame, 2006; Suzuki *et al.*, 2014) and addition of organic manure (Smithson and Giller, 2002) were reported to be more effective in improving soil organic matter content. Variability in soil organic carbon resulting from field-specific management is common among farming systems in Sub-Saharan Africa (Tittonell *et al*., 2005a; 2005b; Bationo *et al*., 2007; Dunjana *et al*., 2012). Differences in organic matter content between rich and poor farmers' fields were previously reported among maize growers in Zimbabwe (Mtembanengwe and Mapfumo, 2008).

The decrease in organic matter with depth has been established (Bationo *et al.*, 2007). However, in this study the effect of soil depth was not obvious. This is possibly due to frequent mixing of soil surface during weeding operations (Tillage). Although, the interaction between sampling time and soil depth showed marginal effect.

Soil total N content was not influenced by fertilizer treatments and farm types but the observed values were within the range reported earlier in the region (Bationo *et al*., 2007; IFDC, 2002; Fofana *et al*., 2008) and in the same area (Suzuki *et al*., 2014). The latter authors evaluated the effect of traditional management practices on nutrient status of Sahelian sandy soil and reported higher total N in the fields close to homesteads where farm yard manure has been applied compared to field that did not receive any organic matter for decades. The general low N content observed in this study could be attributed to low N inputs resulting from the small quantities of applied fertilizer and the poor quality of transported manure (Hayashi *et al.*, 2009).

Soil available P did not show any variation among the fertilizer application and farm type. The observed values were lower than 4.4 and 6.2 mg kg^{-1} reported earlier for compound and bush farms, respectively. The critical value of soil available P required to obtain 90% of the maximum pearl millet yield in the sandy soil of Niger is 8 mg kg^{-1} (Manu *et al*., 1991; Bationo and Kumar, 2002). The low soil available phosphorus content observed on these farms can be explained by the low rate of P inorganic fertilizer commonly used by farmers in the ongoing field trials since only a micro-dose quantity of 0.4 g of P is placed strategically per hill. One of the most important factors responsible for deficiency in available P in acid sandy soils is its chemical binding as Fe or Al phosphate (Amberger, 2006).

The higher K content observed at the beginning of the growing season compared to that at the end of the season could be as a result of K supply through household manure and crop residue left on the field. K has been reported to be supplied through manure and crop residues which could explain the relatively higher amount observed on top farms as compared to the bottom farms. The positive relationship of K with the stability of aggregate (Figure 4.7) is indicative of higher amendments effects on soil structure with increase in K supply as in top farm compared to bottom farm type. Hafner *et al*. (1993) attributed the beneficial effects of exchangeable K to its direct supply through millet straw. 'Farm by farm type' explained most of the variability in exchangeable K observed among treatment.

Fallow fields showed higher organic carbon, N and available P contents (Appendix 2) than the cultivated soil. However, exchangeable potassium content (Appendix 2) on fallow field was lower than on cultivated soil. Higher exchangeable K content on cultivated fields can results from amendment such as millet straw and manure additions.

5.3.1 Effects of fertilizer application and farm types on millet leaf P and K concentrations

Millet leaf P concentration generally decreased with growth stages, with the tillering stage having the highest level, followed by the flowering stage and the maturity stage. The low level of P at maturity stage was expected as nutrients are being translocated from steam and leaf to reproductive organs. Moreover, the influence of growth stages on millet leaf P concentration changed with farm type in the two growing seasons suggesting that amendment application and farm type affected millet leaf P concentration at different growing stages. Scott-Wendt *et al*. (1988a) reported variation in critical nutrient concentration in millet with growth stage and indicated that poor growing plant had deficient concentrations of P and K and potential toxic level of Mn. However, Maman *et al*. (2000) reported no influence of low and high managements (manure and fertilizer) on millet N and P concentrations and higher translocation of nutrients from stem and leaves to panicles in higher rainfall year.

The observed millet leaf total P concentration at flowering stage was within the range reported earlier. Gupta (1981) reported that P concentrations fell from 4 to 1 g kg^{-1} between 20 to 47 days after planting (flowering stage). In this study P, concentrations fluctuated between these growing stages and varied depending on treatment and farm type. At maturity stage grain formation is more favoured by the plant over the leaves during P partitioning, therefore P concentration in leaves decreased significantly. P uptake by millet was influenced by straw application through decreased concentrations of exchangeable Al and enhanced root growth (Hafner *et al*., 1993).

The change in potassium concentration in leaf with growth stages confirmed previous reports (Gupta, 1981; Scott-Wendt *et al*., 1988a). Gupta (1981) reported that K concentration fell from 37 to 10 g kg^{-1} between 20 and 47 days after planting (flowering stage). The higher level of leaf K observed in treated plots over the control was expected as these plots received fertilizer application. However, lower K values were also expected from the DAP treatment since it does not contain K. The difference between top and bottom farm type in leaf K concentration could be explained by higher crop residue and manure level on the top farm type. Beneficial effects of exchangeable K uptake was attributed to direct K supply with millet straw as reported by Hafner (1993) and Subbarao *et al.* (2000). Factors that influence the availability of nutrients are important for optimum use of limited external inputs.

Overall P and K values obtained in this study were comparable to those previously reported by Hafner *et al*. (1993). The authors reported sufficiency range of nutrient concentrations in leaves to vary from 3 to 6 g kg^{-1} for P, and from 30 to 45 g kg^{-1} K in 23 to 39 days-old sorghum plants. Information on the dynamics of macronutrients particularly P are required for simulating millet growth using crop growth model such as DSSAT and APSIM.

5.4.1 Effect of fertilizer application and farm type on millet grain yield

The extent of the increase in millet grain and stubble yields observed in amended plots, over the two growing seasons, relative to control treatment depended on farm type. Top farm produced higher grain yield than the bottom farm type. This performance of the top farm type could be attributed to the relatively higher soil organic matter content which resulted significantly in higher water and nutrient availability. Differences in soil fertility management practices among farmers could have resulted in a gradient in soil organic matter between top and bottom farmers. The results were as previously reported (TSBF, 2002; Adamou *et al*., 2011) where higher millet grain yield in amended plots compared to the control cutting across farmers' field at Karabédji were obtained. Similarly, differences of millet yield were also reported earlier based on farm distance to homestead (Bationo *et al*., 2007; Fofana *et al*., 2008). The authors attributed higher grain yield from infields than outfields to an ISFM-induced drought tolerance of soils of the former farms as result of higher organic matter content.

Relationships between millet grain yield on one hand, and the index of structural stability and plant available water on the other were positive and significant which illustrated the key role played by soil physical properties in yield variation. Moreover, leaf total phosphorus level at maturity was found to be positively correlated with millet grain yield showing higher P in the leaves where grain yield was higher. However, Maman *et al.* (2000) reported higher P concentration in millet straw and leaf in the year with lower rainfall implying that nutrient translocation from leaves to panicles might have been prevented by water stress. Variability in pearl millet yield in this study was also strongly affected by year and difference in farm type.

5.5.1 Discussion on model evaluation between predicted and measured millet grain and stubble yields

The high index of agreement and low RMSE value obtained show that the APSIM model was capable to reproduce millet grain yield reasonably well under control and fertilizer treatments in both farm types. A high coefficient of determination (R^2 = 0.77) was obtained in testing the relationship between observed and predicted millet grain yields (Figure 4.23).

The average d index and RMSE value obtained from the biomass yield confirmed the underestimation of biomass yield which has been noticed in several cases. However, the results can also be considered as satisfactory considering the high degree of relationship between observed and predicted values obtained (R^2 = 0.67) in Figure 4.24. Previous report (Akponiké, 2010) also showed relatively good performance of the APSIM model in reproducing biomass and grain yield of millet in one year and overestimation of biomass yield in the other.

The fact that simulated millet grain and biomass yields using generated-weather data for Karabédji were similar to those obtained using measured weather data at Sadoré shows the practicability of weather generators such as the MarkSimGCM. Qian *et al*. (2011) also reported no statistically significant difference when synthetic data were used to substitute weather data measured on the same study site.

5.6.1 Discussion on socio-economic survey

The high proportion of non-educated farmers shows the low level of formal education of the farming communities in and around Karabédji village. This low education level could be a bottleneck to dissemination of soil fertility management technologies. Education level is an important aspect of the adoption as educated farmers may be more appreciative of the benefits of new technology (Kassie *et al.*, 2012).

Average household size at national level in Niger is 6-10 members; therefore the respondent population reflected exactly the local household characteristics which illustrate the high demographic rate in the country. Niger has one of the world's highest child birth rate (3.7%) and a fecundity of about 7 children per woman (INS, 2012). However, despite the high demographic rate, labour availability remains a main constraint to adoption of new technologies. As the household size increases, labour force is also expected to increase. However, a common practice in the area is the seasonal migration of youth to urban areas and neighbouring countries. This practice has a direct effect on labour availability despite its important contribution to household income; the remittance received from the migrants were used to purchase inputs back home. The seasonally-migrated youth do not come back timely to provide help for the high labour demanding operations at the beginning of the season such as planting and weeding. Therefore, labour becomes scarce and has consequences on the adoption of any technology which requires more labour than the traditional practice such as fertilizer micro-dosing technique. Fertilizer micro-dosing technique has now become a common practice among farmers in Karabédji area.

Fifty seven percent of respondents in the survey population are members of farmer-based organizations (Table 4.34). Membership of FBO improves farmers' awareness and access to soil fertility management technology. This is a channel which extension agents use to select farmers for training and it serves also as an entry point for both government and project interventions. Moreover, FBO farmers are involved in other local initiatives that strengthen exchanges between members and thereby facilitate the passing on of information about new technologies or the availability of farm inputs among farmers.

Farmer typology greatly influenced soil fertility management practices. The highest mean fertilizer was found with farmers who are FBO and demo members but not resource endowed. This shows clearly the importance of FBO and Demo membership, though this category represents only (6%) of the sample population. However, the average quantity of fertilizer used among non-resource endowed farmers who are members of FBO but not demo and representing 32% of the farming population is appreciably good (10 kg ha^{-1}) compared to other categories. The most commonly purchased inputs by farmers are inorganic fertilizer, pesticides, seeds and organic manure. Endowed non demo and FBO members spend more on manure than any other category of inputs.

Results also showed the predominance of low input farmers which illustrates the low input characteristics of the farming systems in Niger. Farming system in Niger has always been classified as low input and subsistence, and has negative impacts on land resources. Farmers depend totally on the land resources which continue to degrade as more is taken from the soils than is restituted. Lower proportion of participant farmers were observed than non-participants in the lowest input category. This shows that participation to demonstration activities, apart from exposing farmers to new soil fertility management practices also indirectly, improves their access to farm inputs. No significant difference ($P > 0.1$) was observed between non-participant and participants in farm income (Table 4.35).

Most farmers in the area apply inorganic fertilizer and organic manure (Table 4.36). The application of organic manure is a common practice by small scale farmers in Karabédji. Other soil and water conservation practices such as mulching, Zai pits and half-moon have also been used by farmers in the area under special conditions (on water and wind erosion-affected areas of the farms). Farmers with more fertile farms left more crop residues at the end of the season. Degraded farms had less quantity of surface residue throughout the dry season which has a serious impact on wind erosion.

Significant mean differences ($P < 0.1$) were obtained between participant and non-participant farmers of demonstration activities in both quantities of inorganic fertilizer and organic manure being applied per ha (Table 4.37). The average quantity of inorganic fertilizer applied was 12 kg ha^{-1} for participant farmers whereas non participant farmers applied 7 kg ha^{-1}. The national average quantity of inorganic fertilizer used by farmers was estimated at 4 kg ha^{-1}. Demonstration activities had great impact not only on farmers' awareness but also on the use of farm inputs.

Lack of purchasing power (lack of credit facility) as farmers' reason for inadequate use of mineral fertilizer illustrates the fact that most of the famers are poor. Abdoulaye and Sanders (2005) reported low market prices of output and high fertilizer cost as major reason for low adoption of new agricultural technologies.

The presence of input shops and warrantage system, which most farmers viewed as best opportunities they have, were initiated to counteract constraints such as low purchasing power, low market prices of produce and fertilizer unavailability. Both input shop and warrantage system were setup during project intervention through the local FBO. The warrantage system enabled farmers to keep their farm produce until market prices became better thereby preventing selling at low prices immediately after harvest. The benefits obtained from warrantage were being used to purchase inputs made available at village level and in small packs for use by farmers. Therefore, it is easier for farmers actively involved in FBO activities or living in or near input shop and warrantage villages to derive more benefits.

CHAPTER SIX

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and conclusions

The purpose of this study was to investigate the implications of changes in physical and hydrological properties of a Sahelian sandy soil under long-term soil fertility management practices and the implications for phosphorus and water availability. The study also aimed at identifying key soil physical quality indices that could help in predicting pearl millet yield using crop growth model.

The results revealed no significant changes in air capacity, specific volume, macro-porosity, relative field capacity, field-saturated hydraulic conductivity and soil sorptivity between fertilizer application and farm types. However, variations in aggregate stability under water drop method were observed between fertilizer rates by farm type interaction - more stable aggregates were found in fertilizer-treated plots than in non-fertilizer-treated plots and on top farm type than on bottom farm type. Moreover, significant positive correlation was obtained between stability of aggregate and soil physical quality index.

The study has also showed changes in soil physical quality index 'S' with depth under different fertilizer rates and farm type and indicated that 'S' matched with the critical values set by Dexter. The Dexter soil physical quality index 'S' can adequately be used to detect changes in soil physical quality of the Sahelian sandy soil although no direct relationship was found between 'S' and pearl millet yield. Plant available water decreased with depth and relatively higher values were recorded in top compared to bottom farm type.

The study indicated that the method for determining soil macro-porosity using soil water retention curve measurement is comparable to the disc infiltrometer method in terms of results. Therefore, the disc infiltrometer can adequately be used to assess changes in soil macro-porosity of the Sahelian sandy soils.

Through this study, the contribution of farm by farm type in explaining observed variability in different soil physical properties was shown. Farm by farm type accounted for most of the observed variability in air capacity, stability of aggregate from water drop and plant available water, whereas no influence of farm by farm type was observed on soil macro-porosity.

Lower organic carbon content was recorded on non-fertilized plots than on fertilizer-treated plots and on top farms than on bottom farm type. The observed values of total N, available phosphorus and exchangeable potassium were generally low and were not much influenced by the fertilizer treatments on both farm types. However, exchangeable K varied with time of sampling and higher values were recorded on top farms than on bottom farm types. Farm by farm type influenced the observed variability in exchangeable potassium.

High variability in millet leaf P concentration was generally noticed among the fertilizer treatments and farm types. The concentrations of total P and K in pearl millet leaf were found to vary significantly between growth stages thereby confirming earlier reports. Millet leaf P concentration varied more with growth stage by farm type over the two growing seasons, whereas variation in total K concentration was more influenced with fertilizer application rates by growth stage.

The study also demonstrated that responses of millet grain and stubble yields to fertilizer rates depended much on farm type and the NPK 15-15-15 + TRP on top farm type consistently recorded the highest values. The difference in farm type explained about 90% of the observed variability in millet yield over the two years of study. Furthermore, significant relationship of pearl millet grain yield with the stability of aggregate and plant available water were found thereby showing the importance of soil physical properties in explaining variations in millet yield.

The study also showed how APSIM model can be used to simulate millet yield using the observed differences in soil properties among farm types under farmer's field condition. APSIM model predicted millet grain and biomass yield with relatively good precision. However, underestimation of biomass yield was noticed. Simulations of millet grain and biomass yields using weather data from the nearest meteorological station gave similar results when compared with generated climatic data for the study site. Thus, the MarkSimGCM weather-generated data can be used to accurately simulate millet grain and biomass yield where measured data are lacking.

Finally, the socio-economic survey carried out during this study presented individual and household characteristics of farmers in the study area. Most farmers did not have formal education, household size between 6-10 members was most predominant and 57% of farmers were members of FBO. Moreover, the average farm input (inorganic fertilizer and organic manure) varied between different categories of farmers. Membership of FBOs and demos, and resource endowment were found to greatly influence the average farm input the farmer applied. Generally, low input farming is practised by farmers and the average quantity of inorganic fertilizer used was 3 to 14 kg ha^{-1} depending on the type.

The study also showed that most farmers viewed lack of purchasing power as their main reason for inadequate use of mineral fertilizers. Decline in rainfall and in soil fertility were also viewed as more threatening factors over farm fragmentation, rapid increase in population and flooding as far as farming activities were concerned. Farmers also viewed input shops, warrantage system and presence of project as the main opportunities that contributed greatly to the betterment of their farming conditions.

6.2 Recommendations

- Effect of fertilizer application was more pronounced with higher management level of the top farm than the bottom farm type. Water and nutrient status of soil were much more favourable for millet production on top farm type. Therefore, the disseminated three fertilizer micro-dosing rates namely DAP, NPK + 15-15-15 at 4 kg P ha^{-1} and NPK 15-15-15 + TRP at 13 kg P ha^{-1} should be used by farmers in combination with practices such as manure application and reduced crop residue removal after harvest for sustainable crop production in the Sahel.

- Government policies towards improved access to farm inputs to the predominantly small scale farmers should be strengthened.

- On-station and on-farm data on nutrient uptake particularly phosphorus and potassium at different growth stages and under different management conditions in the Sahel should be investigated further to improve the sensitivity of crop models to changes in nutrient management in pearl millet.

- Further studies would be required to find critical values for the Dexter physical quality index for the Sahelian Arenosols.

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APPENDICES

Appendix 1.

Appendix 1.1. Mixed model analysis for fertilizer application and farm type effects on soil specific volume

Random term	Component	s.e.	variance (%)
Farm by farm type	0.0000762	0.0000967	11
Residual	0.000605	0.000144	89
Total	0.000681		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.00	1	0.947
Fertilizer treatment	0.60	3	0.897
Depth	0.63	1	0.426
Type x Fertilizer treatment	4.92	3	0.178
Type x Depth	1.05	1	0.307
Fertilizer treatment x Depth	0.54	3	0.911
Type x Fertilizer treatment x Depth	1.93	3	0.587

Appendix 1.2. Mixed model analysis for fertilizer application and farm type effects on soil air capacity at 0-10 cm and 10-20 cm depths

Random term	Component	s.e.	variance (%)
Farm by farm type	0.00035	0.00023	61
Residual	0.000221	0.0000532	39
Total	0.000571		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.05	1	0.831
Fertilizer treatment	1.86	3	0.603
Depth	0.25	1	0.619
Type x Fertilizer treatment	1.12	3	0.773
Type x Depth	0.16	1	0.691
Fertilizer treatment x Depth	0.31	3	0.958
Type x Fertilizer treatment x Depth	1.67	3	0.644

Appendix 1.3. Mixed model analysis for fertilizer application farm type and effects on macro-porosity determined from soil water retention curve

Random term	Component	s.e.	variance (%)
Farm by farm type	-0.0000012	0.00000099	0
Residual	0.0000185	0.00000442	100
Total	0.0000173		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	1	1	0.317
Fertilizer treatment	1.38	3	0.711
Depth	0.65	1	0.420
Type x Fertilizer treatment	0.21	3	0.976
Type x Depth	0.01	1	0.917
Fertilizer treatment x Depth	7.84	3	0.049
Type x Fertilizer treatment x Depth	2.44	3	0.487

Appendix 1.4. Mixed model analysis for fertilizer application and farm type effects on macro-porosity determined from disc infiltration measurements

Random term	Component	s.e.	variance (%)
Farm by farm type	-0.0000007.2	0.0000008.6	0
Residual	0.0000117	0.000003.52	100
Total	0.00001098		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	2.28	1	0.131
Fertilizer treatment	3.62	3	0.306
Type x Fertilizer treatment	0.28	3	0.964

Appendix 1.5. Mixed model analysis for fertilizer application and farm type effects on soil water content at field capacity

Random term	Component	s.e.	variance (%)
Farm by farm type	0.000191	0.000136	40
Residual	0.000283	0.0000676	60
Total	0.000474		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	0.77	1	0.381
Fertilizer treatment	0.43	3	0.934
Depth	0.49	1	0.485
Type x Fertilizer treatment	4.36	3	0.225
Type x Depth	4.21	1	0.040
Fertilizer treatment x Depth	1.49	3	0.684
Type x Fertilizer treatment x Depth	5.08	3	0.166

Appendix 1.6. Mixed model analysis for fertilizer application and farm type effects on soil relative field capacity

Random term	Component	s.e.	variance (%)
Farm by farm type	0.001553	0.001087	46
Residual	0.0018	0.000431	54
Total	0.003353		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	0.31	1	0.577
Fertilizer treatment	0.42	3	0.937
Depth	0.01	1	0.917
Type x Fertilizer treatment	3.61	3	0.306
Type x Depth	2.73	1	0.099
Fertilizer treatment x Depth	0.96	3	0.811
Type x Fertilizer treatment x Depth	4	3	0.261

Appendix 1.7. Mixed model analysis for fertilizer application and farm type effects on the stability index of soil aggregates (water drop method)

Random term	component	s.e.	variance (%)
Farm by farm type	1.346	0.911	54
Residual	1.126	0.189	46
Total	2.472		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	1.86	1	0.172
Fertilizer treatment	4.37	3	0.224
Type x Fertilizer treatment	7.61	3	0.055

Appendix 1.8. Mixed model analysis for Dexter soil physical quality index

Random term	Component	s.e.	variance (%)
Farm by farm type	0.000161	0.000115	37
Residual	0.000273	0.0000618	63
Total	0.000434		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	0.04	1	0.833
Fertilizer treatment	3.67	3	0.299
Depth	357.26	1	< 0.001
Type x Fertilizer treatment	0.95	3	0.813
Type x depth	0.28	1	0.597
Fertilizer treatment x depth	3.51	3	0.319
Type x Fertilizer treatment x depth	1.81	3	0.612

Appendix 1.9. Mixed model analysis for inorganic fertilizer application and farm type effect on plant available water

Random term	Component	s.e.	variance (%)
Farm by farm type	0.000212	0.000147	43
Residual	0.000285	0.000068	57
Total	0.000497		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	0.94	1	0.332
Fertilizer treatment	1.63	3	0.654
Depth	4.10	1	0.043
Type x Fertilizer treatment	4.41	3	0.221
Type x Depth	2.60	1	0.107
Fertilizer treatment x Depth	1.32	3	0.724
Type x Fertilizer treatment x Depth	7.50	3	0.057

Appendix 1.10. Mixed model analysis for fertilizer application, farm type and time of sampling and interactions effects on soil pH in 2012

Random term	Component	s.e.	variance (%)
Farm by farm type	0.18	0.0000	50
Residual	0.18	0.0265	50
Total	0.36		
Fixed term	**Wald statistic**	**Df**	**χ^2 pr.**
Type	0.01	1	0.907
Fertilizer treatment	1.45	3	0.693
Time	70.53	1	< 0.001
Depth	0.27	1	0.603
Type x Fertilizer treatment	0.64	3	0.887
Type x Time	0.77	1	0.380
Fertilizer treatment x Time	0.30	3	0.960
Type x Depth	0.05	1	0.821
Fertilizer treatment x Depth	1.18	3	0.759
Time xm2 Depth	0.34	1	0.562
Type x Fertilizer treatment x Time	0.9	3	0.825
Type x Fertilizer treatment x Depth	0.87	3	0.833
Type x Time x Depth	0	1	0.961
Fertilizer treatment x Time x Depth	1.43	3	0.699
Type x Fertilizer treatment x Time x Depth	0.34	3	0.952

Appendix 1.11. Mixed model analysis for fertilizer application, farm type and interactions effects on soil pH water in 2013

Random term	Component	s.e.	variance (%)
Farm by farm type	0.01633	0.01253	44
Residual	0.0207	0.0069	56
Total	0.03703		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	2.48	1	0.116
Fertilizer treatment	0.99	3	0.804
Type x Fertilizer treatment	2.71	3	0.439

Appendix 1.12. Mixed model analysis for inorganic fertilizer application, farm type and time of sampling effects on organic carbon (2012)

Random term	Component	s.e.	variance (%)
Farm by farm type	0.000153	0.000144	10
Residual	0.00145	0.000221	90
Total	0.001603		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	1.14	1	0.285
Fertilizer treatment	1.41	3	0.704
Time	0.05	1	0.823
Depth	0.36	1	0.551
Type x Fertilizer treatment	0.53	3	0.911
Type x Time	2.77	1	0.096
Fertilizer treatment x Time	3.98	3	0.264
Type x Depth	0.43	1	0.511
Fertilizer treatment x Depth	1	3	0.800
Time x Depth	3.35	1	0.067
Type x Fertilizer treatment x Time	3.52	3	0.318
Type x Fertilizer treatment x Depth	3.12	3	0.374
Type x Time x Depth	0.02	1	0.885
Fertilizer treatment x Time x Depth	1.6	3	0.659
Type x Fertilizer treatment x Time x Depth	6.11	3	0.106

Appendix 1.13. Mixed model analysis inorganic fertilizer application and farm type effects on soil organic carbon content (2013)

Random term	Component	s.e.	variance (%)
Farm by farm type	0.000057	0.000092	10
Residual	0.000493	0.0001256	90
Total	0.000550		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	0.35	1	0.552
Fertilizer treatment	2.81	3	0.423
Type x Fertilizer treatment	1.26	3	0.739

*Treatment means are average of four replicates; depth = 0-20 cm; DAP = Di-ammonium phosphate fertilizer

Appendix 1.14. Mixed model analysis for fertilizer application, farm type and interactions effects on soil total nitrogen content in 2012

Random term	Component	s.e.	variance (%)
Farm by farm type	-0.00000286	0.00000236	0
Residual	0.000019	0.00000776	100
Total	0.000019		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.87	1	0.35
Fertilizer treatment	1.37	3	0.713
Type x Fertilizer treatment	6.9	3	0.075

Appendix 1.15. Mixed model analysis for fertilizer application, farm type and interactions effects on soil total nitrogen content in 2013

Random term	Component	s.e.	variance (%)
Farm by farm type	0.00000322	0.00000259	40
Residual	0.00000488	0.00000163	60
Total	0.0000081		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.19	1	0.666
Fertilizer treatment	1.25	3	0.740
Type x Fertilizer treatment	0.48	3	0.923

Appendix 1.16. Mixed model analysis for fertilizer application, farm type and interaactions effects on soil available phosphorus content in 2012

Random term	Component	s.e.	variance (%)
Farm by farm type	0.059	0.415	2
Residual	2.308	0.769	98
Total	2.367		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.2	1	0.65
Fertilizer treatment	2.58	3	0.46
Type x Fertilizer treatment	1.09	3	0.78

Appendix 1.17. Mixed model analysis for fertilizer application, farm type and interactions effects on soil available phosphorus content in 2013

Random term	Component	s.e.	variance (%)
Farm by farm type	0.1292	0.1574	27
Residual	0.3500	0.1429	73
Total	0.4792		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.46	1.00	0.50
Fertilizer treatment	0.14	3.00	0.99
Type x Fertilizer treatment	1.01	3.00	0.80

Appendix 1.18. Mixed model analysis for fertilizer application, farm type and interactions effects on soil exchangeable potassium content in 2012

Random term	Component	s.e.	variance (%)
Farm by farm type	0.0014374	0.0010416	84
Residual	0.0002790	0.0000759	16
Total	0.0017164		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	2.46	1	0.116
Fertilizer treatment	3.58	3	0.311
Time	57.53	1	< 0.001
Type x Fertilizer treatment	0.45	3	0.929
Type x Time	0.92	1	0.338
Fertilizer treatment x Time	2.03	3	0.566
Type x Fertilizer treatment x Time	3.16	3	0.368

Appendix 1.19. Mixed model analysis for fertilizer application, farm type and interactions effects on soil exchangeable potassium content in 2013

Random term	Component	s.e.	variance (%)
Farm by farm type	0.0014479	0.0009414	67
Residual	0.0007180	0.0002392	33
Total	0.0021659		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	1.64	1	0.200
Fertilizer treatment	2.18	3	0.537
Type x Fertilizer treatment	3.65	3	0.302

Appendix 1.20. Mixed model analysis for fertilizer application, farm type and interaction effects on millet leaf total P content in 2012

Random term	component	s.e.	variance (%)
Farm by Growth stage	0.00567	0.00401	36
Residual	0.0101	0.00221	64
Total	0.01577		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Growth_stage	30.58	2	< 0.001
Fertilizer treatment	1.81	3	0.613
Type	3.71	1	0.054
Growth_stage x Fertilizer treatment	9.9	6	0.129
Growth_stage x Type	7.21	2	0.027
Fertilizer treatment x Type	1.03	3	0.794
Growth_stage x Fertilizer treatment .Type	8.32	6	0.216

*Treatment means are average of four replicates

Appendix 1.21. Mixed model analysis for fertilizer application, farm type and interactions effects on millet leaf total P content in 2013

Random term	component	s.e.	variance (%)
Farm by Growth stages	0.000236	0.00025	9
Residual	0.00227	0.000404	91
Total	0.002506		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Growth_stage	147.82	2	< 0.001
Fertilizer treatment	11.71	3	0.008
Type	1	1	0.317
Growth_stage x Fertilizer treatment	11.87	6	0.065
Growth_stage x Type	17.78	2	< 0.001
Fertilizer treatment x Type	4.38	3	0.223
Growth_stage x Fertilizer treatment x Type	1.61	6	0.952

*Treatment means are average of four replicates

Appendix 1.22. Mixed model analysis for fertilizer application, types and interactions on plant leaf total K content in 2013

Random term	component	s.e.	variance (%)
Farm by farm type	0.1586	0.0848	48
Residual	0.17	0.0303	52
Total	0.3286		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Growth_stage	31.89	2	< 0.001
Fertilizer treatment	14.61	3	0.002
Type	16.2	1	< 0.001
Growth_stage x Fertilizer treatment	21.08	6	0.002
Growth_stage x Type	3.36	2	0.186
Fertilizer treatment x Type	4.04	3	0.257
Growth_stage x Fertilizer treatment x Type	2.55	6	0.862

*Treatment means are average of four replicates

Appendix 1.23. Mixed model analysis for fertilizer application, farm type and interaction effects on millet grain yield in 2012

Random term	Component	s.e.	variance (%)
Farm by farm type	68352	40155	93
Residual	4781	1594	7
Total	73133		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	6.42	1	0.011
Fertilizer treatment	71.11	3	< 0.001
Type x Fertilizer treatment	10.05	3	0.018

Appendix 1.24. Mixed model analysis for fertilizer application, farm type and interaction effects on grain yield in 2013

Random term	Component	s.e.	variance (%)
Farm by farm type	107278	63595	90
Residual	11440	3813	10
Total	118718		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	4.01	1	0.045
Fertilizer treatment	30.01	3	< 0.001
Type x Fertilizer treatment	1.67	3	0.643

Appendix 1.25. Mixed model combined analysis for fertilizer application, farm type and interactions effects on grain yield

Random term	Component	s.e.	variance (%)
Farm by farm type by year	1953	24717	92
Residual	33692	7352	8
Total	440351		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	9.94	1	0.002
Year	3.02	1	0.082
Fertilizer treatment	67.19	3	< 0.001
Type x Year	0.24	1	0.622
Type x Fertilizer treatment	7.09	3	0.069
Year x Fertilizer treatment	17.07	3	< 0.001
Type x Year x Fertilizer treatment	1.2	3	0.753

Appendix 1.26. Mixed model analysis for fertilizer application and farm type effects on millet stubble yield

Random term	component	s.e.	variance (%)
Farm by Type by year	406659	252869	92
Residual	33692	7352	8
Total	440351		
Fixed term	**Wald statistic**	**d.f.**	**χ^2 pr.**
Type	126.3	1	< 0.001
Fertilizer treatment	24.54	3	< 0.001
Year	1.58	1	0.208
Type x Fertilizer treatment	2.12	3	0.549
Type x Year	0.14	1	0.711
Fertilizer treatment x Year	12.78	3	0.005
Type x Fertilizer treatment x Year	0.42	3	0.937

Appendix 2. Physical and chemical properties of fallow fields (0-20 cm) at Karabédji, Niger

Parameters	Mean*	Se
Particle Size Distribution (g kg^{-1})		
Clay (< 2 µm)	57.3	6.5
Silt (2-50 µm)	37.5	2.8
Sand (50-2000 µm)	905.3	7.1
Bd (Mg m^{-3})	1.58	0.011
PAW (mm)	13.75	0.250
pH	6.02	0.074
OC (g kg^{-1})	1.41	0.04
N (mg kg^{-1})	201	24.0
P (mg kg^{-1})	3.95	0.50
K (cmol kg^{-1})	0.054	0.010

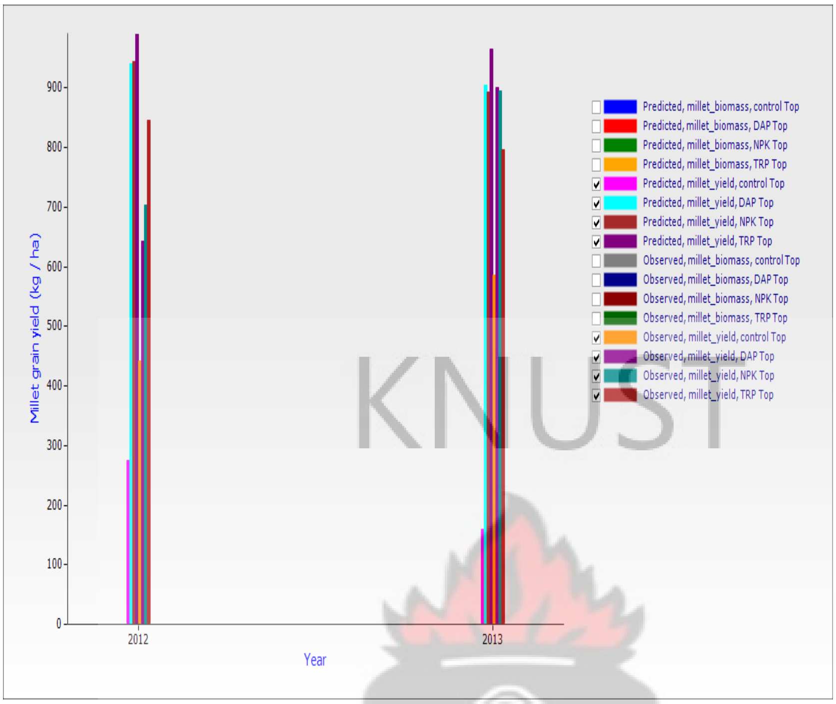
*Values are average of four fields under long-term (> 10 years) fallow; Se = standard error

Appendix 3. Model parameters for millet cultivar Haini Kirey

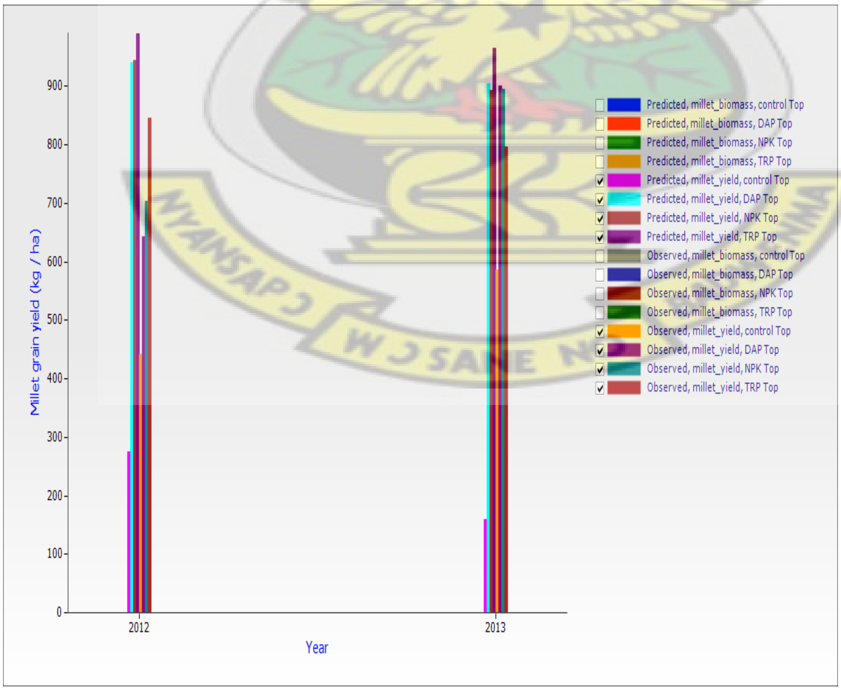
Parameters	Value	Units
est_days_emerg_to_init	17	°C days
tt_emerg_to_endjuv	796	°C days
pp_endjuv_to_initp	112.4	°C days
tt_flower_to_maturity	400	°C days
head_grain_no_max	2600	°C days
grain_gth_rate	0.5	mg grain^{-1} day^{-1}
tt_flag_to_flower	150	°C days
tt_flower_to_start_grain	112	°C days
tt_maturity_to_ripe	1	

Source: Akponikpe (*et al*. 2010)

Appendix 4. Model outputs for simulated grain and biomass yields

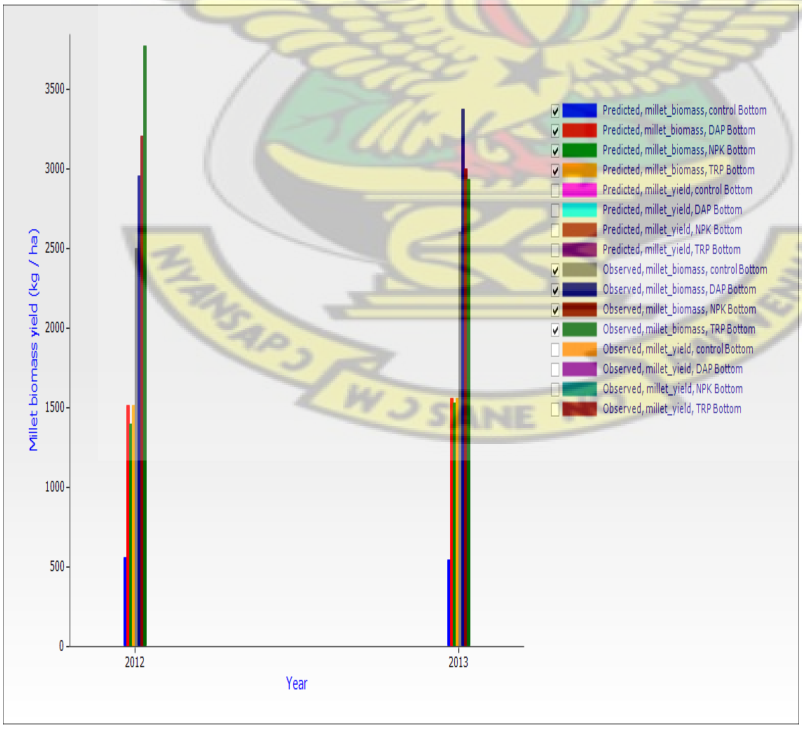


Predicted and observed millet grain yield for control and fertilizer treatments in top farm types in Karabédji, Niger. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.

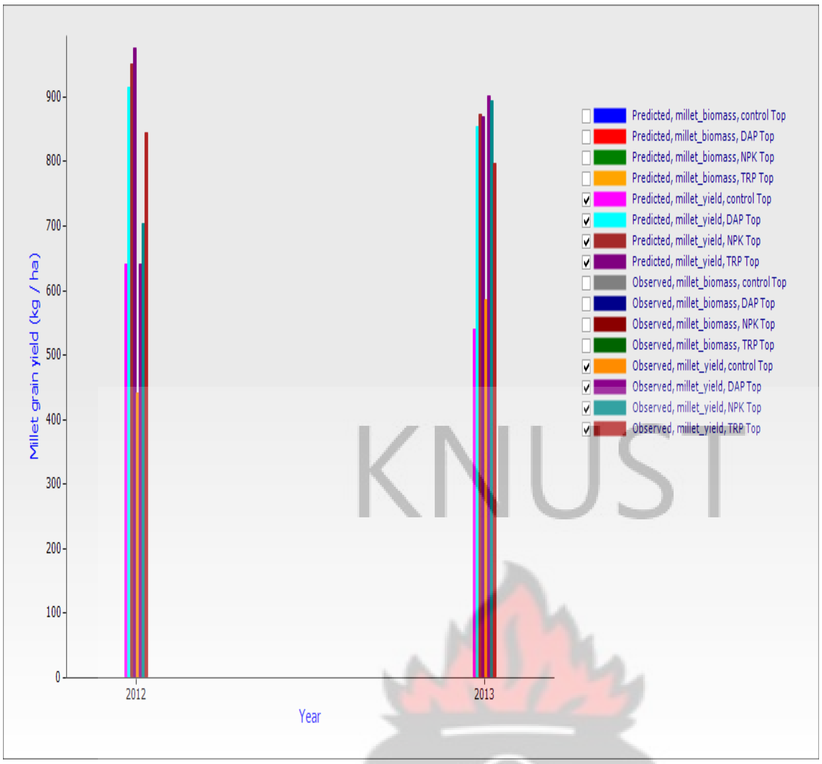


Predicted and observed millet grain yield for control and fertilizer treatments in bottom farm types in Karabédji, Niger. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.

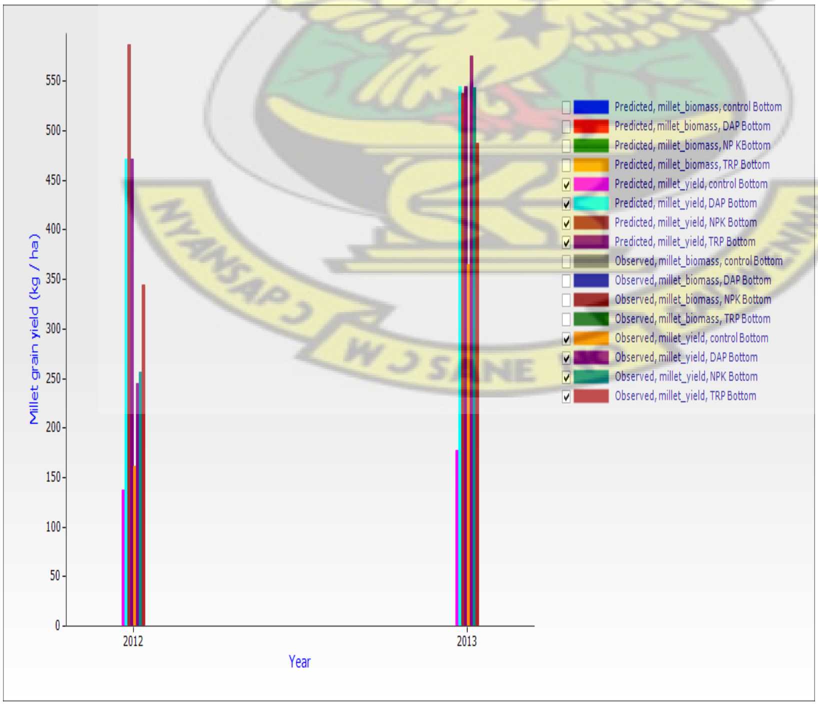
Predicted and observed millet biomass yield for control and fertilizer treatments in top farm types, Karabédji, Niger. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.



Predicted and observed millet biomass yield for control and fertilizer treatments in bottom farm types, Karabédji, Niger. N.B.: first four bars in each year represent predicted values whereas the last four bars are observed.

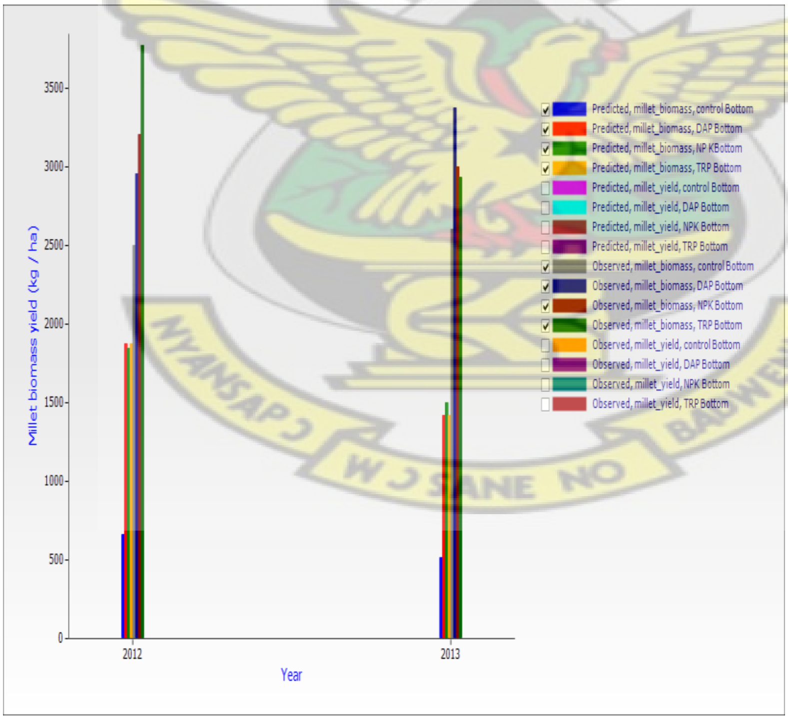


Predicted and observed millet grain yields for the control and fertilizer treatments in top farm types using generated climatic data. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.



Predicted and observed millet grain yields for the control and DAP treatments in bottom farm types using generated climatic data. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.

Predicted and observed millet biomass yield of the control and fertilizer treatments in top farm types using generated climatic data, Karabédji, Niger. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.



Predicted and observed millet biomass yield of the control and fertilizer treatments in bottom farm types using generated climatic data, Karabédji, Niger. N.B.: first four bars in each year are predicted values whereas the last four bars are observed.

Appendix 5. Questionnaire used for socio-economic survey

A. Specific objective

To establish the relationships between farmers' socio-economic conditions and soil fertility management. (French: Identifier les relations entre les caractéristiques socio-économiques des producteurs et la gestion de la fertilité).

B. Personal information

Name of the respondent

Name of the head of household

Sex: Female Male

Marital status: i) Married ii) Single iii) Divorced iv) Widow (er)

Educational level of the head of the household

i) Primary ii) Secondary iii) University iv) Qur'an v) Literacy vi) Other

Farm ownership status

i) Own ii) Rent iii) Family iv) Loan against security v) Share- cropping vi) More than one

Affiliation to a farmers' association

Yes or no

Origin:

Native or migrated

C. Household information

Number of person in the household

Age groups	0-6 yrs	7-14 yrs	15-20 yrs	21-50 yrs	> 50 yrs
Female					
Male					

Do you use hired labour on your farm?

yes or no

If yes,

i) Family ii) Salary iii) Both.

If salary,

Temporary? or Permanent?

Can you estimate your annual farm income?

How much did you spend on farm input purchase last year?

Did you purchase fertilizer?

Yes No

If yes, can you estimate how much you spent last year in purchasing Urea? ____________FCFA

Can you estimate how much you spent last year in purchasing NPK? ____________FCFA

Can you estimate how much you spent last year in purchasing organic fertilizer? _____FCFA

If you use family labour to collect organic fertilizer, how many hours did you use to collect it?

How many hours you spent to transport it?

How many hours you used to apply it in the farm?

D. Farmer's endowment

How many of each animal below do you have?

Animals / birds	Yes	No	If yes no.	Total value
Cows				
Calves				
Donkey				
Horses				
Goats				
Sheep				
Hens/Birds				
Others				

How many of each material below do you or your family owns?

	Yes	No	Number	Total value (CFA
Ox-driven cart				
Donkey-driven cart				
Ox-plough				
Donkey –plough				
Radio				
TV				
Motorcycle				
Bicycle				
Barrow				
Telephone				
Others				

Can you give us information on your land properties to complete the table below?

Farms	Surface	1 = own	Distance from	Position
1				
2				
3				
4				
5				
6				

Do your wives have farms? Which size?

E. Farm management practices

Do you apply chemical fertilizer in your farm?

Yes No

If yes, which fertilizer do you use?

Which quantity for each one?

Did you buy all those fertilizers? Yes No

Which quantity did you buy for each one? And when?

Which technique did you used to apply your fertilizer?

If you use micro-dosing technique, when do you apply the fertilizer? At planting Two weeks after planting other (specify)

Do you apply organic fertilizer? Yes or No

If yes which types of organic fertilizer do you apply? Household manure, millet straw or other specify?

Among the following management practices which one you do not often carry out on time?

Planting Weeding Thinning Fertilizer application Pest control

Which special management practice are you using on your farm which is different from what other people are doing?

Is there any constraint preventing you from using mineral fertilizer properly?

yes or no

If yes, which among the following?

Lack of money

Unavailability of fertilizer

Don’t know how to use it

Other (specify)

What types of agricultural equipment do you use?

i) Hoes ii) animal plough iii) tractor

Which among the following changes affect you most:

i) Decline in rain fall ii) Soil fertility decline iii) Fragmentation of farms

iv) Increase in population v) Flooding vi) Others

Which among the following points enhanced your life farming conditions?

i) Presence of project ii) Municipality iii) Farmers associations iv) Input shop v) Warrantage system vi) Others