ASSESSING THE POTENTIAL OPTIONS FOR IMPROVING CROP YIELD AND

WATER USE EFFICIENCY IN THE SAHELIAN LOW INPUT MILLET-BASED CROPPING SYSTEM

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1 ASSESSING THE POTENTIAL OPTIONS FOR IMPROVING CROP YIELD AND WATER USE EFFICIENCY IN THE SAHELIAN LOW INPUT MILLET-BASED CROPPING SYSTEM

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DOCTOR OF PHILOSOPHY

IN
SOIL SCIENCE

By

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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 acknowledgment has been made in the text.

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''Education is the most powerful weapon which you can use to change the world.'' Nelson Mandela

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Abstract

Soil amendments are often unavailable in adequate quantities for increased crop production in the Sahelian smallholder cereal cropping systems. In order to increase crop yields and encourage farmers to apply inorganic fertilizers, fertilizer microdosing technology was developed. This technology has given promising results in respect of crop yields improvement, fertilizer use efficiency and economic returns. However, many scientific reports have cautioned that crop nutrients uptake under micro-dosing technology could be markedly greater than what was applied through the technology. There, is therefore, an urgent need for critical assessment of the potential mining effect of fertilizer micro-dosing in order to develop supportive strategies for further improvement of the efficient use of limited resources of smallholder farmers. The objectives of this study were to (1) explore the mechanisms governing the growth enhancing phenomena of the fertilizer micro-dosing technology, (2) assess the potential effects of integrated use of organic amendments and fertilizer micro-dosing in improving millet yield and water use efficiency and (3) evaluate the extent of nutrient gains and losses under fertilizer micro-dosing by estimating the associated nutrient balances. To achieve these objectives, three field experiments were conducted in Niger during the 2013 and 2014 rainy seasons. The first experiment comprised two options of fertilizer micro-doing (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) with the broadcast of 200 kg NPK ha^{-1} which is the blanket recommended rate of fertilizer in the study area. The second experiment consisted of the factorial combination of two fertilizer micro-dosing options with three rates of manure (1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}) and method of their applications (hill placement and broadcasting). The third experiment involved two fertilizer micro-dosing options and three organic mulches (millet straw, *Acacia tumida* pruning and manure). The most important findings that emerged from these experiments were that growth parameters (leaf area index, leaf chlorophyll content and root length density) were markedly increased with fertilizer micro-dosing at the early stage of millet growth compared with the broadcast of 200 kg NPK ha^{-1}. The millet grain yield under fertilizer micro-dosing combined with manure increased on average by 59%, 83% and 113% for 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1} of manure inputs, respectively in comparison with fertilizer microdosing alone. These increases in grain yield were accompanied by marked increases in water use efficiency. Hill placement of manure increased total dry matter on average by 23% and water use efficiency by 35% relative to that of manure broadcasting. The partial nutrient balances were -37 kg N ha^{-1}yr^{-1}, -1 kg P ha^{-1}yr^{-1}, -34 kg K ha^{-1}yr^{-1} in plots that received the application of 2 g DAP hill^{-1} and -31 kg N ha^{-1}yr^{-1}, -1 kg P ha^{1}yr^{-1}, -27 kg K ha^{-1}yr^{-1} for the 6 g NPK hill^{-1} treatment. The partial nutrient balances were exacerbated by the nutrient export in straw yields which accounted for on average 66% N, 55% P and 89% K of total export. The annual full nutrient balances with fertilizer micro-dosing treatments were on average - 47 kg N ha^{-1} yr^{-1}, -7 kg P ha^{-1} yr^{1} and -22 kg K ha^{-1} yr^{-1} which represented 7%, 24% and 10% of N, P and K stocks, respectively. Combined application of fertilizer micro-dosing with organic mulch increased millet grain yield by 37%. The millet grain yield increases relative to the unmulched control were 51% for manure, 46% for *A. tumida* mulch and 36% for millet mulch. The addition of *A. tumida* pruning, manure and millet straw mulch to fertilizer micro-dosing increased water use efficiency of millet by on average 55%, 49% and 25%, respectively. These results indicate that the positive effect of fertilizer microdosing in increasing millet yield results from the better exploitation of soil nutrients due to early lateral roots proliferation within the topsoil. In addition, millet production with the fertilizer micro-dosing technology can be improved further by hill-placement of manure. However, the increase in yields with fertilizer micro-dosing was accompanied by an increase in soil nutrients uptake which resulted in negative nutrient balances. These results have important implications for developing an agro-ecological approach to address sustainable food production in the Sahelian smallholder cropping systems.

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Introduction

Chapter One

I. General introduction

1.1. Problem statement and justification

Agricultural production in Sub-Saharan Africa is characterized by a low level of productivity resulting from inherent low soil fertility and continual decline in soil fertility due to poor soil management and other biophysical factors (Voortman, 2010). In large parts of sub-Saharan Africa, many studies have shown that soils are rapidly degraded which consequently affects food production and threatens food security (Stoorvogel and Smaling, 1990; Heano and Baanante, 1999; Bationo *et al.*, 2007). According to Lal (1988), more than 50% of the Sahelian soils are degraded and are not suitable for agricultural purposes.

Agricultural production in Niger is predominantly rainfed. Low availability of soil nutrients and unpredictable rainfall patterns are major interacting constraints for agricultural production in Niger resulting in frequent food shortage and persistent poverty within smallholder farmer communities (Payne *et al.*, 1992; Bationo *et al.*, 1998b; Bationo *et al.*, 2003; Gandah *et al.*, 2003a).

To increase crop yields and improve the efficient use of scarce rainfall in the Sahelian zone of Niger, the use of mineral fertilizer is becoming more necessary (Payne, 1997, 2000). The blanket fertilizer recommendation in Niger is 200 kg ha^{-1} of compound NPK (15-15-15) (Hayashi *et al.*, 2008). However, most of the farmers cannot afford to buy such a quantity of fertilizer. The high price of inorganic fertilizer, the limited resource endowment of small-scale farmers, and the risk associated with its application in the dry spell prone areas, are the most limiting factors for low fertilizer use in Niger (Abdoulaye and Sanders, 2005).

Fertilizer micro-dosing is a technology developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and partners aimed at reducing the quantity of fertilizer application drastically (ICRISAT, 2009). Fertilizer micro-dosing or “micro-fertilization” consists of the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing (Hayashi *et al.*, 2008; ICRISAT, 2009). Reports have shown that the implementation of this technology resulted in improved nutrient use efficiency, increased crop yield and higher economic returns (Bationo and Buerkert, 2001; Tabo *et al.*, 2007). Consequently, it has become a most common soil fertility management option for small-scale farmers across sub-Saharan West Africa (Buerkert and Schlecht, 2013). However, many scientific reports have cautioned that crop nutrients uptake under micro-dozing technology could be markedly greater than what was applied through this technology (Buerkert *et al.*, 2001; Camara *et al.*, 2013). This implies that fertilizer micro-dosing could cause a further depletion of soil nutrients in these fragile soils. There, is therefore, an urgent need for critical assessment of the potential mining effect of fertilizer micro-dosing in order to develop supportive strategies for achieving improved and sustainable productivity of the technology.

On the other hand, the effectiveness of integrated use of mineral and organic amendment in improving crop yields and maintaining soil fertility sustainably has been well documented (Yamoah *et al.*, 2002; Bationo *et al.*, 2003; Akponikpé *et al.*, 2008). However, the availability of the resources for achieving these positive effects remains a major challenge, especially in the Sahelian countries. The main sources of organic amendments such as crop residue and animal manure are not available in adequate quantities. For instance, the competing uses of crop residues make their use for agricultural purposes difficult and thereby limit their availability for use as soil amendment (Bationo *et al.*, 1995; Valbuena *et al.*, 2014). Animal manure is the most common organic resource for smallholder farmers but its availability in sufficient quantities is also a major challenge (de Ridder and Van Keulen, 1990; McIntire *et al.*, 1993). There, is therefore, a need for exploring alternative options to address these constraints for improving the efficient use of the limited resources of small-scale farmers for increased food production. This thesis seeks to answer the following research questions:

i. What are the determinants of fertilizer micro-dosing induced yield increase of millet?
ii. What are the potential effects of repeated cultivation under current fertilizer micro-dosing practice on soil nutrients reserves?
iii. What are the potential options for improving the efficient use of limited resources (inorganic fertilizer, organic amendments and rainwater) of smallscales farmers?
iv. Will the integrated use of fertilizer micro-dozing with organic amendment increase millet yields and maintain soil nutrient levels?

1.2. Objectives

The main objective of this research was to assess the sustainability of fertilizer microdozing in millet-based cropping system and identify an appropriate option that will improve sustainably the productivity of this technology.

The specific objectives of this study were to:

i. determine the mechanisms of fertilizer micro-dozing induced millet yield increment;
ii. assess the potential of integrated use of fertilizer micro-dosing and manure in improving millet yield and water use efficiency; iii. evaluate the extent of nutrient gains and losses under fertilizer micro-dosing by examining nutrient balances in millet-based cropping system. iv. establish the mulching effect of *Acacia tumida*

prunings on millet yield and water use efficiency under fertilizer micro-dosing technology.

1.3. Description of study area

Niger is a landlocked country of the Sahel and covers an area of 1 267 000 km^2 with a total of 17 138 707 inhabitants (Abdoul Aziz *et al.*, 2014). Agricultural production in Niger is rainfed and the cultivated lands are situated essentially within a 150 km wide band in the south of the country (Fig. 1.1). The agricultural regions extend from the Sahelian zone in the North (annual rainfall average > 350 mm) to the more favorable zone for crop production, which is the Sudanian zone at the extreme south of the country with the annual rainfall average between 600 and 800 mm (Pender *et al.*, 2008). The length of the growing period (75 to 120 days) is decidedly reliant on the beginning of rains which varies from year to year (Sivakumar *et al.*, 1993). The soils in the agricultural zones of Niger are preponderantly sandy, low in organic matter and moisture-holding capacity, and deficient in both nitrogen and phosphorus with the latter being the most limiting nutrient (Bationo and Mokwunye, 1991b). Soil nutrient deficiency and unreliable rainfall are the major limiting factors for agricultural activities in Niger (Gandah *et al.*, 2003b). The current study was carried out at the ICRISAT, Research Station in Sadoré located at 13˚ 15’ N and 2˚ 18’ E, 240 m above sea level in the Sahelo-Sudanian agro-ecological zone of Niger (Figure 1.1).

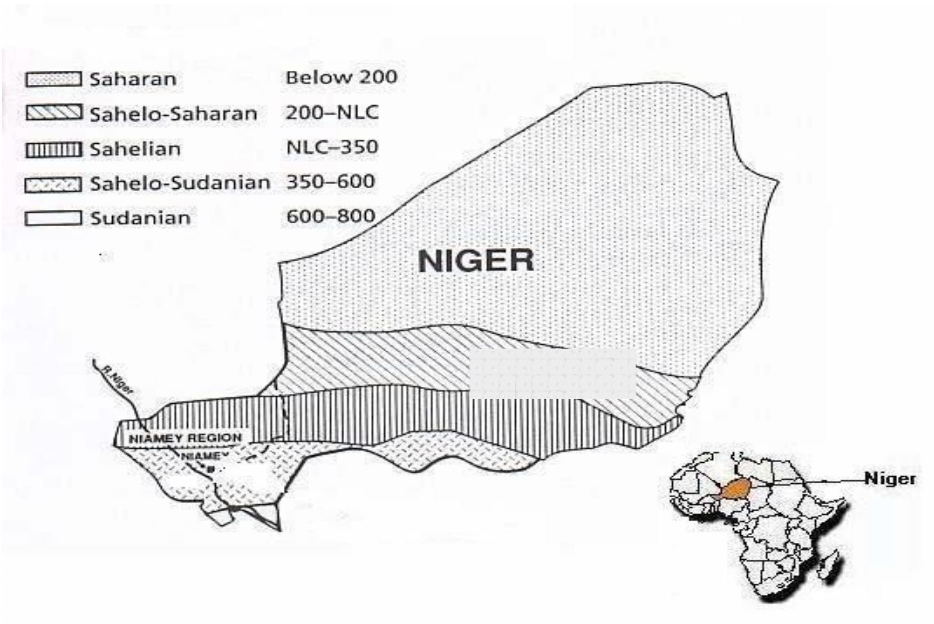

Figure 1. 1. Agro-ecological zones of Niger
Source: Adapted from Pender *et al.* (2008) NLC
= northern limit of cultivation.

1.4. Outline of the thesis

This thesis is made up of seven chapters following this introductory chapter. The chapter two reviewed the main developments in soil fertility management for increased yields in low-input millet-based cropping systems in Sahelian areas. Chapter three discusses the determinants of fertilizer micro-dosing induced yield increment of pearl millet. Chapter four addresses the potential of combined application of fertilizer microdosing and manure to improve millet yield and water use efficiency. Chapter five deals with the nutrient balances under fertilizer micro-dosing while the potential of *Acacia tumida* mulches for increasing millet yield and water use efficiency under fertilizer micro-dosing is presented in Chapter six. Chapter seven provides the general discussion of the main findings described in the different sections of Chapter four and finally Chapter eight provides the conclusions and recommendations emanating from the study.

Chapter Two

Increasing crop yield and water use efficiency in low input millet-based cropping systems in Sahelian zone of Niger: Review

Chapter Two

2.0. Literature Review

Increasing crop yield and water use efficiency in low input milletbased cropping systems in Sahelian zone of Niger

2.1. Role of organic amendment in low input based farming systems

Soil organic matter plays a crucial role in sustaining agricultural production by improving soil structure, acting as nutrient reservoir and regulating the availability of soluble nutrients to plants (Bationo *et al.*, 2007; Marenya and Barrett, 2009). Soil organic carbon plays an important role in ensuring good health of the soil environment and is critical in providing needed ecosystem services (Bationo *et al.*, 2007). Diverse practices have been employed to increase soil organic carbon stocks in West Africa. The use of organic amendment is traditionally the main practice of soil fertility and soil organic matter maintenance in the Sahelian low input-based farming systems (Harris, 2002). The benefits of organic amendment in agriculture are multi-folds. Organic amendment application, increased soil organic matter and microbial populations, that improves aggregate stability thereby increasing soil water holding capacity and reduces erosion losses (Palm *et al.*, 2001). Yet, the increment in soil organic matter through organic amendment takes decades because of the rapid oxidation particularly in the dry areas where the high temperatures speed up the processes of organic matter degradation (Bationo *et al.*, 2003). However, in some studies, increase in soil organic matter has been observed depending on the amount of organic residues returned into the soil. In a long-term crop residues management study conducted in Niger, Bationo and Buerkert (2001) reported that the levels of soil organic carbon at 10 cm soil depth were 2.0 g kg^{-1} and 3.3 g kg^{-1}, respectively for 2

Mg ha^{-1} and 4 Mg ha^{-1} mulching plots with crop residues compared to un-mulched plots (1.7 g kg^{-1}). However, the continuous cultivation resulted in a drastic reduction of soil organic carbon content (Bationo *et al.*, 2007). These authors reported that for the sandy soils, the average annual losses in soil organic carbon may be as high as 4.7%, whereas for sandy loam soils, losses seem much lower at an average of 2 %.

Therefore, for restoring soil organic matter and enhancing soil fertility to increase crop yields, various sources of organic amendments are applied in the Sahelian areas (Bationo and Mokwunye, 1991b; Schlecht *et al*., 2006).

2.1.1. Effect of crop residues in soil fertility maintenance and crop yield improvement

The contribution of crop residues applied as surface mulch or incorporated into the acid sandy soils of Niger in increasing crop yields has received much attention. Many studies have reported significant increases in millet yield in response to the application of crop residues. In a study conducted in Niger, Buerkert and Lamers (1999) observed an increase in millet grain yield of 20%, 108% and 283%, respectively when 2000 kg ha^{-1} of crop residues were applied annually for three years. In the same area and with the same crop residue application rate, Buerkert *et al.* (2002) reported an increment in millet grain yield of 6%, 20% and 40%, respectively in first, second and third experimental year. Doubling the rate of crop residue applied into the soil led to an increase in millet grain yield of 250% (Bationo and Mokwunye, 1991b). On acid sandy soil in Niger, Rebafka *et al.* (1994) reported that application of crop residues increased total dry matter yield of pearl millet by more than 60% whereas removal of crop residues decreased yields immediately. In another study, the application of all crop residues from the last annual harvest during an eight-year long-term experiment in Niger led to an increase in millet yield from 40% to 238% (Yamoah *et al.*, 2002).

However, the positive effect of crop residue application on crop yields depends on the level of fertility of the plots. For instance, Buerkert and Stern (1995) reported that millet responded positively to crop residue application on low productivity plots whereas little response was observed on high productivity plots.

Changes in soil nutrients concentrations have been reported in response to crop residue application. Data on phosphorus recovery from crop residue show that phosphorus concentration in the soil solution was about three times higher with crop residue application than where this material was removed (Kretzschmar *et al.*, 1991; Hafner *et al.*, 1993). According to Bationo *et al.* (1993), returning the crop residues to the soil resulted in significant reduction of nutrients export especially, Ca, Mg and K.

Increase in crop yields with crop residues has been explained by many mechanisms including increase in root growth (Kretzschmar *et al.*, 1991; Hafner *et al.*, 1993), increase in soil biological activity (Mando and Brussaard, 1999), protection of seedlings from the effects of wind erosion, and improved water availability at the onset of the growing season (Buerkert *et al.*, 2000). Bationo *et al.* (1995) argued that the mechanisms responsible for the positive effect of crop residue on crops yields were influenced by factors including local conditions such as rainfall, wind speed, soil type and temperature regime.

The major limitation of all these studies explaining the positive effects of crop residues and the mechanisms underlining these effects is that the quantity of crop residue that leads to all these conclusions is rarely available on farmers' fields. For instance, in a study conducted in Niger, Baidu-Forson (1995) showed that the quantity of millet straw produced in the Nigerien smallholder farmers was around 1200 kg ha^{1}. Considering the rates used on Research Stations, the significance of all these studies for the farmers was limited because they could not apply such recommended rate of crop residues.

Strictly speaking, retaining crop residues as it is recommended to the Sahelian farmers particularly in Niger is a daunting challenge because of the competing use of this material for animal grazing, fencing of houses and firewood. Furthermore, the economic benefit derived from the alternative use of crop residues (feeding animal, fuelling and building) is higher than that from the relative increase in yield due to the retention of crop residues on the field (Opoku, 2011). It is also important to note that the farmers who are interested in what to eat tomorrow are less interested in the fact that leaving crop residue will prevent their soils from wind erosion, trap dust and thereby maintain soil fertility. Therefore, to tackle the problem of crop residues scarcity, there is the need to find other sources of organic amendment that can be easily adopted by Sahelian smallholder farmers to maintain soil fertility and attain sustainable food production.

The contribution of existing agro-forestry trees as mulch and their comparative mulching effects with the most commonly applied organic amendment (crop residues and manure) are not, however, very well documented in the semiarid area of Niger. For instance, *Acacia tumida* is one of the Australian *Acacias* introduced and tested in the early 1980s in Niger with the primary intention to improve food security (Rinaudo *et al.*, 2002). This species produces good seed yields and provides other products and services such as soil fertility improvement through nitrogen fixation and leaves for mulching. *Acacia tumida* tree is pruned once a year (with a total foliar biomass of 8 Mg ha^{-1}) and their branches spread over the field add organic matter and other nutrients to the soil (Rinaudo and Cunningham, 2008). There is, however, limited information on the potential mulching effects of *A. tumida* mulch in low-input smallholder cereal based cropping systems in Niger. The exploration of the potential mulching effects of this agro-forestry will be of utmost importance in the biomass-scarce areas where the availability of mulching materials is a challenge.

Animal manure, another farm-available soil amendment, is an important organic input in African agro-ecosystems. Animal manure has a similar role as crop residue mulching for the maintenance of soil productivity and maintenance of crop yields (Bationo *et al.*, 2007). The potential of manure in maintaining soil fertility and enhancing crop production has been intensively investigated (Bationo and Mokwunye, 1991c; Brouwer and Powell, 1998; Williams, 1999).

2.1.2. Effect of manure on crop yields and soil fertility maintenance

Traditionally, manure plays an important role in soil fertility maintenance in the Sahelian smallholder farming systems. Manure is a source of soil nutrients (macro and micro-nutrients), and is beneficial to soil physical properties (Harris, 2002). Many other studies have shown that manure application increases crop yields, augments soil organic matter content, ameliorates soil pH, improve soil nutrients status and soil water holding capacity (Bationo and Mokwunye, 1991c; Powell and Williams, 1993; Bationo *et al.*, 1998b; Schlecht and Buerkert, 2004).

The management of manure is extremely important to ensure its quality, as the methods of storing manure can also affect their nutrient contents (Ewusi–Mensah, 2009). Storage of manure may encourage loss of nitrogen, mainly by volatilization. In Ghana, Kwakye (1980) found that up to 59% of nitrogen was lost after a storage period of three months. Given the variability in manure quality, and in the soil to which it is applied, recommendations for its use must be very site-specific (determined with respect to soil and source of manure) otherwise the adoption of the technology may be unsuccessful.

Consequently, many attempts have been made to provide answers to several research questions concerning manure use for soil fertility maintenance in the Sahel. The earlier studies focused on the availability of manure to increase sustainably food production in the Sahelian zones (McIntire *et al.*, 1992; Williams *et al.*, 1995) while other investigations addressed the issues related to the manure placement strategies and allocation among different fields (Bationo *et al.*, 1998b; Fatondji, 2002; Gandah *et al.*, 2003a).

Studying the effect of the application of various rates of cattle and sheep manure with and without urine on the efficient use of nutrients for millet production in the Sahelian area of Niger, Brouwer and Powell (1995) observed that manure application increased millet growth and termite activity which accelerated the decomposition of manure. Collecting data from manure application on millet in the South-West of Niger, Brouwer and Powell (1998) showed that within twelve months of application of cattle manure at the rates similar to those of farmers' fields (9 to 10 Mg ha^{-1}) on average, 91 kg ha^{-1} of N and 19 kg ha^{-1} of P were leached to between 1.5 m to 2 m depth. In the same study, these authors observed that the greater leaching losses were attained in the lowest and wettest plots on concave slopes than the driest plots on convex slopes. The variability of soil properties within fields poses a challenge to farming in terms of nutrient management. To increase manure use efficiency in the sandy soils, it was, therefore, suggested that manure should be applied at different parts of a farmer's field at the rates not exceeding 2500 kg ha^{-1} in accordance with the micro-topographical changes (Brouwer and Powell, 1998). The rates of return on such application rates have been estimated several times. Williams *et al.* (1995) found that such application resulted in yield increases in the order of 20 to 60 kg ha^{-1} cereal grain, and 70 to 178 kg ha^{-1} straw. More specifically, Agyemang *et al.* (1993) determined yield increases of 45 kg of cereal grain per tonne of manure applied to sorghum, and 30 kg of cereal grain per tonne of manure applied to millet.

The scarcity of manure within farmers' community makes farmers to adopt their own strategies to improve the efficient use of this material. The localized application of manure in more responsive field area instead of broadcasting it in the entire field is one of the strategies used by smallholder farmers in the Sahel. The most promising technique for increasing manure use efficiency is through Zaï, which is one of water harvesting techniques used to rehabilitate the degraded land in the Sahelian zone (Fatondji, 2002). This technique has been advocated to improve nutrient and water use efficiency thereby increasing crop yield (Fatondji *et al.*, 2006). However, this technique requires further labour investment for digging the Zaï but this did not affect the adoption of this technique by the smallholder farmers since the activity is carried out during the dry season when the field harvests have been completed (Wildemeersch *et al.*, 2013).

Corralling during which animals are left overnight to graze freshly harvested millet fields is also a common manure management practice used in Niger (De Rouw and Rajot, 2004; Schlecht and Buerkert, 2004). This practice leads to the deposition of huge quantity of manure combined with urine. Gandah *et al.* (2003a) observed that between 1.5 to 17 Mg ha^{-1} of manure are left in the fields through corralling with cattle. Data collected on corralling in the Fulani and Zarma villages in South-western Niger, show an average application rate of 12.7 to 15.5 Mg ha^{-1} of faecal dry matter for cattle and 6.8 to 7.2 Mg ha^{-1} for sheep and goats (Schlecht and Buerkert, 2004). However, in the same area, lower amount of manure addition through corralling (0.05 to 4.9 Mg ha^{1}) was reported by Akponikpè (2005). These figures indicate that the application rates of manure through corralling differ according to the size of animals owned by the farmer and also the extent of manure distribution in the field depends on the farmer's capacity to ensure good distribution of the manure in the spots during corralling (Akponikpè *et al.*, 2014).

Although manure plays an important role in maintaining soil fertility in semi-arid area of Niger, many factors influence the application of this material by the farmers. Analysing the cultural and socio-economic factors affecting manure use decision, Williams (1999) showed that farmer's own herd size, contractual arrangements between herders and farmers for manure, seasonal migration and its effect on livestock investment and the proportion of cultivated land owned by the farmer are the major factors that affect positively farmers' manuring decision. The other factors found to negatively affect manure use are the farm size, distance of field to the homestead, the proportion of the cultivated land recently under fallow and land-labour ratio (Williams, 1999).

In semi-arid West Africa, farmers complain about the shortage of organic material for composting, and a shortage of fodder for livestock (Williams *et al.*, 1995). Several researchers have calculated the amount of manure required to replace the nutrients removed from fields by cropping, and have tried to calculate the number of livestock required to produce that amount, and hence, the rangeland required to support them (Schlecht *et al.*, 1993; Turner, 1994). The general conclusion is that once cropping intensity reaches a certain level, there is, insufficient rangeland to provide the fodder necessary to support the livestock required to provide sufficient manure for the fields (Harris, 2002). Consequently, many authors argue that there will never be sufficient manure available to maintain soil fertility (de Ridder and Van Keulen, 1990; McIntire and Powell, 1995). The use of mineral fertilizers is, therefore, promoted as an alternative to manure use, and is often recommended as one way of resolving the problems of nutrient-poor farming systems in Africa (McIntire and Powell, 1995).

2.2. Effect of mineral fertilizer on millet yields

The application of mineral fertilizer is essential for optimizing plant growth rates and yield levels whereas non-use of mineral fertilizer leads to a dramatic expansion and the extension of the agricultural area even on degraded lands (Bindraban *et al.*, 2014). In many countries, however, plant growth is limited by the lack of soil nutrients more severely than by lack of rainfall, even in semi-arid regions where water availability would be considered as the main limiting factor (Giller *et al.*, 2006; Twomlow *et al.*, 2011). For instance, Bindraban *et al.* (1999) reported that nutrient-limited yields are approximately 1–2 Mg ha^{-1} in the Sahelian region, even though the total amount of rainwater would allow yield levels up to 4-5 Mg ha^{-1}. This implies that the use of fertilizers is crucial for closing crop yield gaps (Mueller *et al.*, 2012).

Soil nutrient deficiencies especially in P and N have been reported among the major constraints of crop growth on degraded Sahelian sandy soils (Scott Wendt *et al*., 1988). The research in mineral fertilizer strategies for increasing crop yields has, therefore, generally focused on satisfying plant N and P demands which are the two most limiting nutrients on weakly buffered West African Soils (Bationo *et al.*, 2003). Potassium (K) is generally not considered a limiting nutrient for millet productivity in the Sahelian zone of Niger, in part because of substantial potassium inputs from Harmattan dust (Herrmann *et al.*, 1996). However, Rebafka *et al.* (1994) have reported large responses to K fertilizer in the absence of crop residue application. In addition, Voortman *et al.*

(2004) pointed out the importance of K in explaining spatial variability of crop growth. Furthermore, after a two-year continuous millet cropping in a trial with a long-term application of crop residues and mineral fertilizers in Niger, Hafner *et al.* (1993) observed the potassium deficiency in the soil as limiting for optimal millet production. This suggests that apparently the potassium supply through atmospheric deposition and application of crop residues/compost were not sufficient to meet millet potassium requirement for higher grain yield formation.

According to Fofana *et al.* (2008), application of phosphorus fertilizer alone led to steadily and substantial grain and straw yields increases. Even though, several studies support the view that P availability is key for millet production on weakly buffered, acid sandy Sahelian soils (Manu *et al.*, 1991; Bationo *et al.*, 1992), the highest grain yield was obtained at highest N and P application rates. According to Michels and Bielders (2006), 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. These indicate that both N and P are key factors to millet production with P being the most limiting. The response of millet to N fertilization was only palpable when fertilizer P is applied. This was confirmed by a study conducted in Niger by Bationo and Ntare (2000) which demonstrated that traditional millet cowpea rotation in Sahel does not increase millet yields unless inorganic N and P fertilizers are added and suggested a cropping system that integrates millet-legume rotation and a mixture of N and P fertilization as an appropriate alternative for restoring soil fertility on degraded soils.

The effects of mineral fertilizer (either positive or negative) on millet yields have been very well documented in the Sahel (Bationo and Mokwunye, 1991b; Bationo and Buerkert, 2001; Bationo *et al.*, 2003; Muehlig-Versen *et al.*, 2003). However, the use of mineral fertilizer is still very low in Sahelian millet based farming system. According to the African Fertilizer Summit (2006), the fertilizer consumption in 55% of SSA countries including Niger is less than 5 kg ha^{-1}. In order to encourage farmers to use mineral fertilizer, ICRISAT and partners have developed fertilizer micro-dosing technology.

2.2.1. Effect of fertilizer micro-dosing on crop productivity

Several studies have examined the immediate millet or sorghum response to fertilizer micro-dozing in the Sahel. Muehlig-Versen *et al.* (2003) showed that in Niger, hill application of 5 kg P ha^{-1} led to 65% of the yield increase obtained with 13 kg P ha^{-1} broadcast, resulting, therefore, in a significant increase in fertilizer-use efficiency. Abdou *et al.* (2012) reported consistently significant increase in pearl millet yield following strategic placement of 4 kg P per hectare as NPK 15-15-15 or DAP (Diammonium phosphate) at planting. Similar effects have been previously reported from the application of 4 kg P ha^{-1} as compound NPK fertilizer (Bationo *et al.*, 1998b). Other studies in Niger have shown that application of 6 g NPK fertilizer per hill can more than double millet yields (Bationo and Buerkert, 2001) and there is a positive economic return to the use of fertilizer (Hayashi *et al.*, 2008; Tabo *et al.*, 2011). Having tested this technology in three Sahelian countries (Niger, Mali and Burkina Faso), Tabo *et al.* (2007) showed that, on average grain yields of millet and sorghum were greater by 44 to 120% while the farmers' income increased by 52 to 134% when using hill application of fertilizer compared to the earlier recommended fertilizer broadcasting methods and farmers' practice. However, the application of these rates of fertilizer needs one additional person at the time of sowing for fertilizer application. The labour demand at sowing period is high which can lead to delayed sowing thereby resulting in yield decrease. Recent on-farm research in Niger has shown that farmers can delay the application of fertilizer under micro-dosing technology from 10 to 60 days after sowing without significantly reducing the yield and the economic returns (Hayashi *et al.*, 2008).

Recently, Ibrahim *et al.* (2014) showed that increasing the depth of fertilizer microdosing application from 5 to 10 cm results in a marked increase in millet yields. It was postulated that the positive effect of fertilizer micro-dozing can probably be attributed to a root-growth stimulating effect of phosphorus fertilization as previously reported by Aune and Bationo (2008) and Buerkert and Schlecht (2013). There is, however, no empirical evidence that explains the root growth dynamics under fertilizer microdosing. There is, therefore, a need to elucidate the root mechanisms underlying the growth enhancing phenomena of the fertilizer micro-dozing technology.

Although, all the above cited reports indicate that fertilizer micro-dosing increases crop yields and fertilizer use efficiency, Buerkert *et al.* (2001) cautioned that the application of 0.9 g N together with 0.4 g P in NPK to each planting hill constitutes only 10 and 20% of millet plant's total N requirements. In addition, Muehlig-Versen *et al.* (2003) noticed that low rates of phosphorus placement can be easily adopted by the smallholder farmers, but it could not sustain soil's P reserves. This probably explains in part why the issue concerning the sustainability of fertilizer micro-dosing is becoming a matter of debate within the scientific community. Camara *et al.* (2013) argued that fertilizer micro-dosing complied with all except agronomic sustainability, because in the long term it may cause nutrient depletion of the soil and consequently decrease soil fertility and crop productivity. However, some scientists consider this claim an exaggeration (Buerkert and Schlecht, 2013; Aune and Coulibaly, 2015). According to these authors, the increase in grain yield reported from micro-dosing ranging from 240 to 300 kg ha^{-1} on sandy soils across a broad range of climatic and soil conditions in West Africa (Bagayoko *et al.*, 2011) is not high enough to push the alarm on mining effect of fertilizer micro-dosing. From their estimation, an increase of 100 kg ha^{-1} grain yield removes about 2.4 kg N ha^{-1} and 0.29 kg P ha^{-1} (given that the grains contain 15% of protein and 3 g P kg^{-1}). Therefore, a typical increase of 300 kg ha^{-1} of grain yields removes about 7.2 kg N ha^{-1} and 0.87 kg P ha^{-1}. This nutrient removal rate is lower than the quantity of N and P applied in 60 kg NPK ha^{-1} (15-1515) corresponding to 6 g NPK per hill. Even with 2g DAP per hill the phosphorus balance is positive. However, the most important limitation of this argument lies in the fact that the authors overlooked the nutrients removal from straw yield which is at some extent higher than the nutrient exported from grain yield. It seems too simplistic to focus merely on partial nutrient balance to judge the sustainability of a technology. There is scanty information about the mining effect of the micro-dosing technology based on a full nutrient balance and also taking into account what is available in general stock of nutrients. Therefore, there is a need to establish whether fertilizer microdosing is sustainable or not, using better indicators of sustainability.

On the other hand, lone application of mineral fertilizers increased crop yield but the results from long-term experiments indicated that yields declined following continuous application of only mineral fertilizer (Schlecht *et al.*, 2006). The decline in crop yields due to continuous use of inorganic fertilizer might have resulted from many mechanisms such as lowering the base saturation and aggravation of soil acidification, mining of nutrients as higher grain and straw yields remove more nutrients than were added, increased loss of nutrients through leaching and decline in soil organic matter (Bationo *et al.*, 2007). It has also been noted that combined application of inorganic fertilizer with organic material can neutralize the negative effects of the mineral fertilizers (de Ridder and Van Keulen, 1990).

2.2.2. Effect of combined use of mineral fertilizer and organic amendment on crop yield

A large and growing body of literature has investigated the specific effects of manure, crop residues and mineral fertilizer on soil fertility maintenance and crop yield increase in the Sahel (Brouwer and Powell, 1995; Buerkert and Lamers, 1999; Yamoah *et al.*, 2002; Fatondji *et al.*, 2006). However, the availability of these materials in sufficient quantities is a challenge. The integrated soil fertility management defined as *the application of soil fertility management practices and the knowledge to adapt these to local conditions, which maximize fertilizer and organic resource use efficiency and crop productivity* (Sanginga and Woomer, 2009) has been promoted and advocated to preserve soil quality while promoting its productivity. Earlier, this soil fertility management practice had been considered a prerequisite for the achievement of productive and sustainable agriculture production systems (Akponikpe, 2008).

The effectiveness of integrated use of mineral and organic amendment in improving crop yields and maintaining soil fertility has been well documented in the Sahelian low input millet-based farming system. In Niger, Bationo *et al.* (2003) reported that phosphorus use efficiency for millet increased by 46 and 86, respectively for inorganic P applied alone and on plots amended with inorganic fertilizer (N and P) and crop residue. In an earlier study, Yamoah *et al.* (2002) reported that the combination of crop residues and mineral fertilizer gave greater yields and economic returns over fertilizer cost with sustainability yield index higher than that of either crop residue or fertilizer. In a study aimed at developing guidelines for integrated nutrient management, which rely on the potential nutrient sources of manure, pearl millet residue and mineral fertilizers in the Sahel, Akponikpe (2008) found that the effect of manure and residue were additive, as was the effect of manure and fertilizer. No third order interaction existed among residue, manure and mineral fertilizer according the results reported by these authors.

Although, the benefits of combining application of organic and inorganic fertilizers in the subsistence farming systems of Niger have long been appreciated (Bationo *et al.*, 1993; Hafner *et al.*, 1993; Bationo and Buerkert, 2001), the limited access of these materials has hindered the adoption of this technology (Haigis *et al.*, 1999). There is, therefore, a need to find an option that encourages small farmers to make an integrated use of their limited resource to achieve optimal resources use efficiency thereby enhancing food production. In evaluating the effect of fertilizer micro-dosing in combination with five manure practices through corralling, Manyame (2006) reported that the micro-dosing technology was effective in raising pearl millet yield only under low fertility. According to this author, manuring particularly corralling, had the greatest effect on the yield and water use of pearl millet. The most important limitation of the study lies in the fact that no significant interaction between manure and fertilizer micro-dosing was observed. Furthermore, the quantity of manure applied through corralling (8 Mg ha^{-1}) is not generally available in most subsistence farming systems because manuring is strictly limited by households' resource endowment, especially in relation to livestock (Schlecht and Buerkert, 2004). In a study aimed at investigating organic inputs and farmers' management strategies in millet fields of western Niger, the same authors reported that manure application and livestock corralling were the most effective tools to enhance soil fertility. However, these practices were used to less than 30% of the surveyed fields.

2.3. Effect of soil fertility management on crop water use efficiency

In drylands rain-fed regions, water has been long considered to be the main limiting resource for crop growth and yield (Mandal *et al.*, 2007). Although water is limiting, it is often the distribution of water in space and time rather than lack of total seasonal amounts that affects crop growth and final yields in the Sahelian zone (Monteith, 1991). Improved water use efficiency (WUE) is one of the major potential for increasing crop productivity in limited water supply conditions. According to Hatfield *et al.* (2001), water use efficiency represents a given biomass or grain yield per unit of water used by crop.

Water use efficiency can be increased by water conservation measures such as suppression of evaporation, control of weeds, irrigation scheduling, and breeding for increased leaf area. It has been also shown that WUE can be increased by raising soil nutrients levels. The increase in WUE due to increasing soil nutrients availability has been attributed mainly to a larger ratio of transpiration to evapotranspiration as a result of greater leaf area (Schmidhalter and Studer, 1998). According to the same authors, nutrients influence leaf area duration, leaf growth and senescence and thus transpiration. Nitrogen and phosphorus deficiencies can reduce cell expansion which results in small leaves. Generally, adequate fertilized soils promote both rapid leaf area expansion, thus increasing transpiration, and more rapid ground cover, thus reducing evapotranspiration.

In general, WUE is improved with increasing plant nutrient availability as long as water availability is sufficient to provide reasonable growth rates. Several studies have demonstrated that plants growing under nutrient deficiency used water less efficiently than adequately fertilized plant (Andersen *et al.*, 1992). Increasing the availability of plant nutrients increased yields as well as water use by the crop; however, the increase in water use was generally less than 25% (Schmidhalter and Studer, 1998). The earlier study by Carlson *et al.* (1959) showed that the maize yields were doubled primarily by N fertilizers whereas transpiration varied by less than 10 percent. This supports the conclusions reached long ago by Viets (1962), indicating that in most cases when water supply was fixed any factor that increased yield would increase WUE because evapotranspiration would be little affected by the management. Payne (1997), found that higher biomass yields resulting from high rates of fertilizer hardly increased ET in the Sahel. In the Sahelian zone of Niger, Sivakumar and Salaam (1999), have reported that fertilizer application resulted in a small increase in total water use (7 to 14%). These authors explained that it was possible the small increase in water use (ET) could have resulted from increased depth of water extraction. Under the harsh climatic conditions and the sandy soils in Niger, nearly all the plant available water was used by the crop and since evapotranspiration losses were largely controlled by meteorological conditions, seasonal ET is nearly the same whether yields are high or low (Sivakumar and Salaam, 1999). Early development of canopy cover helps the crop to intercept more radiation, increase root development and allocate more of the water extracted by the roots to transpiration. Under the system of pocket planting in the Sahel with wide spacing between planting pockets, soil evaporation losses can be high. Fechter *et al.* (1991), showed that direct evaporation from the soil in the traditional field planted to pearl millet can be between 35 to 45% rainfall. The strategies such as use of fertilizer which can promote rapid early growth can contribute to the reduction of soil evaporation losses and increased WUE. Water use efficiency is mostly influenced by changes in crop yield in response to soil nutrient status or fertility management. This shows once more the need to improve soil fertility in order to achieve greater WUE in millet-based rain-fed systems (Akponikpé *et al.*, 2008).

Increasing or optimising yields by adequate fertilizer increases transpiration efficiency. Plant and soil N status play a role in WUE. Nitrogen fertilization increased crop water use efficiency (Davis, 1994). In the West African Sahel, pearl millet production is constrained by low erratic rainfall and low soil nutrient, particularly P availability. Payne *et al.* (1992) demonstrated the positive effect of P on pearl millet production and water use efficiency. In sandy soils, low K content is often exposed to intermittent periods of drought owing to the low water holding capacity of the soil (Andersen *et al.*, 1992). According to these authors, water use efficiency for total dry matter production was increased by K application; however, grain production was unaffected by the level of K application. In the Sahelian zone of Niger, Sivakumar and Salaam (1999) reported an average increase of 84% in WUE due to the addition of fertilizer. These authors showed that even at the drier areas in the Sahel, application of fertilizer could help to increase the amount of water transpired thereby contributing to increased crop productivity.

The application of fertilizers to increase evapotranspiration and water use efficiency in the Sahelian millet cropping systems is, however, a challenge because of low income of farmers which cannot allow them to afford to buy the adequate quantities of inorganic fertilizers. Fertilizer micro-dosing which is the application of small quantity of fertilizer is becoming the most applied technology by the smallholder farmers in the Sahel (Buerkert and Schlecht, 2013). From the researcher-managed farmer field trial in Fakara, Niger, Manyame (2006) has reported that the fertilizer micro-dosing technology did not increase evapotranspiration in pearl millet cultivated on sandy soils of the study area. Rapid root growth and desired architecture development play an important role in nutrients and water acquisition by the plants in low soil fertility and dry environments. However, the study conducted in Fakara, did not provide any information about the crop rooting systems in order to understand the possible response of crop root growth dynamics to the localized application of small amount of mineral fertilizer on crop water use. Therefore, there is a need to ascertain, if the nutrients applied through fertilizer micro-dosing in low fertility Sahelian sandy soils are large enough to cause changes in rooting systems and consequently, improve crop water use efficiency.

2.4. Summary of literature review

It has been noted from the review that, several studies have been conducted to improve soil fertility and increase yields in the Sahelian small-scale cropping systems. These studies focused mainly on the application of organic amendments and mineral fertilizer either alone or in combination. Although promising results have been reported, the adoption of the soil fertility management technologies developed is still low as a result of limited resource endowment of small-scale farmers. At the moment, fertilizer micro-dosing appears to be the most attractive technology applied by small-scale farmers across sub-Saharan West Africa because of its advantages in increasing nutrient use efficiency, crop yields and economic return. However, the scarcity of information on the nutrient gains or losses has led to excessive emphasis being placed on crop yields and economic income as the direct benefits from the fertilizer microdosing technology. There is, therefore, a need to establish whether fertilizer microdosing is sustainable or not, given that the small dose of mineral fertilizer applied results in greater crop yields thereby high nutrient uptake and export. Furthermore, there is no empirical evidence that suggests that changes in root growth dynamics under fertilizer micro-dosing is one of the mechanisms underlying the root growth enhancing phenomena of the fertilizer micro-dozing technology. The current study aims at bridging these knowledge gaps.

Chapter Three

General Methodological Approach

Chapter Three

3. General materials and methods

This chapter provides detailed description of the methods used for soil moisture measurement and laboratory protocols for soil and plant materials analyses.

3.1. Measurement of soil moisture

The soil moisture content was monitored weekly with a neutron probe (Didcot Instrument Company Limited, Station Road Abingdon, Oxon OX143 LD) through the help of 2 m long access tube installed in each experimental plot (treatment). The measurements were taken at 15 cm interval from 0 to 200 cm depth in all the plots. Before the measurements, the neutron probe had been calibrated in-situ using the gravimetric method as described by the manufacturer. The regression equations at different soil depths resulted from the calibration of the neutron probe were:

Soil depth: 0 to 15 cm $y \square 49.081\ 1.4961 \square x$ [3.1]

15 to 30 cm $y \square 53.82 \square 0.0247x$ [3.2]

> 30 cm $y \square 57.17 \square 0.0868x$ [3.3] where

y is the soil volumetric soil water content; x is the ratio of the neutron probe reading to the standard count, which is the reading of a tube installed in pure water.

3.1.1. Calculation of volumetric soil water

The data collected with the neutron probe were used to calculate the volumetric soil water content with the formula used by Fatondji (2002) as follows:

$$\Theta_v = a + b\left(\frac{C}{Cs}\right) \quad [3.4]$$

where Θ_v is volumetric water content expressed in %; a is the intercept of the equation of the neutron probe calibration curve; b is the slope of the equation; C is neutron count read with the probe in the field and Cs is a standard count reading from the access tube installed in pure water.

3.1.2. Calculation of the stock of water

The stock of water was calculated according to the movement of water at different soil depths using the formula used by Fatondji (2002). From 0 to 15 cm soil depth, the stock of water was calculated as follows:

$$Sw\,(mm) = \frac{\Theta_v}{100} \times (\Delta z \times 10) \quad [3.5]$$

At soil depth > 15 cm, the stock of water was calculated as follows:

$$Sw\,(mm) = \frac{\Theta_v(a) + \Theta_v(b)}{200} \times (\Delta z \times 10) \quad [3.6]$$

where *Sw (mm)* is the stock of water within the soil depth in millimeter; Θ_v is the volumetric water content in %; Δz is the depth of the soil (Δz was multiplied by 10 to convert it in mm); Θ_v *(a) is* the volumetric water at depth *a*; Θ_v *(b)* is the volumetric water at depth *b*.

3.1.3. Calculation of drainage

The drainage was determined using the method developed by Klaij and Vachaud (1992). This method divides the water balance into two phases. In the first phase, applicable earlier in the season, water flux across the maximum depth of probe measurement (Zm) is assumed negligible. Drainage (D) was calculated from the change in soil water content (Ɵ) between the bottom of the root zone (Zr) and Zm, thus allowing calculation of unsaturated hydraulic conductivity *K (Ɵ),* from the flux across Zr. In the second phase, applicable when soil water starts to percolate across Zm, the drainage was calculated from *K (Ɵ),* assuming a hydraulic head gradient (∇H) of - 1.

The drainage was calculated using formula as follows:

$$D(mm) = -K(\theta) \cdot \nabla H \cdot \Delta t \qquad [3.7]$$

where D is the drainage at rooting zone, *K (θ)* is unsaturated hydraulic conductivity at *Zr*; ∇H is the hydraulic head gradient at *Zr*; Δt is the time period between two consecutive neutron probe readings.

According to Klaij and Vachaud (1992) if during a time interval for the conditions of the first phase, the amount of water stored between the plane Zr and the maximum depth of the measurement (Zm) increased by the changes in the amount of water stored in the profile, the same amount of water must have drained through the plane therefore a single K-*Ɵ* value of the hydraulic conductivity function can be estimated. The unsaturated hydraulic conductivity K (θ) from neutron probe readings was thus calculated as follows:

$$K(\theta_a) = -D_r / (\nabla H \, \Delta t) \qquad [3.8]$$

where θa is the arithmetic mean of the soil water content at the beginning (t = t) and end of the time interval ($t = t + \Delta t$) measured at Zr; D_r is soil moisture content below the root zone; ∇H is the hydraulic head gradient at Zr; Δt is the time period between two consecutive neutron probe readings. Using the equation [3.8], and repeating the calculation for different period allow to establish the regression function of the form:

$$K(\theta) = a\theta_a^{\,b} \qquad [3.9]$$

where a and b are constants from the regression equation.

The established $K(\Theta)$ function will thus allow to calculate the drainage beyond the root zone once the soil water content at the maximum depth of measurement begins to increase.

3.1.4. Calculation of the evapotranspiration

The Runoff at the experimental field was assumed to be negligible because of the sandy texture of the experimental field and the slope was less than 2 percent. The evapotranspiration was thus derived from the equation used by Payne (1997) as follows:

$$\Delta S = R - (ET + D) \qquad [3.10]$$

where ΔS is the change in soil water storage in the root zone; ET is evapotranspiration; R is rainfall and D is the root zone drainage.

3.2. Analysis of chemical and physical soil properties

3.2.1. Determination of pH-H_2O

The pH was potentiometrically measured in the suspension of a 1:2.5 soil: liquid mixture (van Reeuwijk, 1993). Ten grams (10 g) portion of soil was weighed into a plastic flask and 25 mL of distilled water was added. The suspension was stirred mechanically and allowed to stand for 30 minutes after which the pH was measured. Before the measurements, the pH meter (Hanna Instruments Ltd, Carrollton, Taxas) was calibrated using buffer solutions of pH 4 and 7. The same procedure was used for pH-KCl, in which the potassium chloride solution 1*M* (KCl) was used instead of distilled water.

3.2.2. Exchangeable acidity

The ions H^+ and Al^{3+} released on exchange by an unbuffered KCl solution was determined using the method described by van Reeuwijk (1993). Ten grams (10 g) portion of soil sample was weighed into a plastic flask and 25 mL of 1 *M* KCl solution was added (with two blanks included). The suspension was stirred mechanically and allowed to stand for 30 minutes and then filtered through a Whatman N^o 42, filter paper. The percolated aliquot was pipetted into 250 mL Erlenmeyer flask then 3-5 drops of phenolphthalein solution were added. Thereafter, the solution was titrated with 0.025 *M* NaOH until the colour turned just permanently pink. The exchangeable acidity was calculated as follows:

$$Exchangeable\ acidity\ (cmol\ kg_c^{-1}\ soil) = \frac{(a - b) \times M \times 4 \times 100 \times mcf}{S} \quad [3.11]$$

Where:

a = mL NaOH needed for the percolate b

= mL NaOH needed for the blank

M = molarity of NaOH

S = air-dry weight of the sample in gram

4 = aliquot factor mcf = moisture

conversion factor

3.2.3. Determination of organic carbon

Organic carbon content of soil was determined using *Walkley-Black* procedure described by van Reeuwijk (1993). This involved a wet combustion of organic matter with the mixture of potassium dichromate ($K_2Cr_2O_7$) solution and sulphuric acid. Five grams (5 g) portion of air-dried soil was weighed in 500 mL Erlenmeyer flask and 10 mL of 0.1667 *M* potassium dichromate ($K_2Cr_2O_7$) solution were added and the mixture stirred gently to disperse the soil. Then twenty milliliters (20 mL) of concentrated H_2SO_4 (95%) were added to the suspension which was shaken gently and allowed to stand for 30 minutes on an asbestos sheet. Thereafter, 250 mL of distilled water were added. This was followed by the addition of 10 mL of concentrated (85%) orthophosphoric acid (H_3PO_4) and 1 mL of diphenylamine indicator. 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 carbon (OC) was calculated as follows:

$$\% OC = \frac{M(V_1 - V_2) \times 0.39 \times mcf}{S} \qquad [3.12]$$

where:

M = molarity of $FeSO_4$ (from blank titration)

V1 = volume of $FeSO_4$ required for the blank,

V2 = volume of $FeSO_4$ required for the soil sample,

S = weight of soil sample in gram

$0.39 = 3 \times 10^{-3} \times 100\% \times 1.3$

3 is the equivalent weight of carbon and 1.3 is the compensation for the incomplete combustion of the organic matter in this procedure.

3.2.4. Determination of total nitrogen

The total nitrogen was determined by the Kjeldahl digestion and distillation method as described by Houba *et al.* (1995). A one gram portion of soil was put into a Kjeldahl digestion flask of 75 mL and 2.5 mL of Kjeldahl catalyst (mixture of 1 part Selenium powder + 10 parts $CuSO_4$ + 100 parts Na_2SO_4) was added and mixed carefully. The stirred mixture was placed on a hot plate and heated to 100 ˚C, for 2 hours. The flasks were removed from the plate and allowed to cool after which 2 mL of H_2O_2 were added and the mixture was heated again at 330 ˚C for four hours until clear and colourless digest was obtained. The volume of the solution was made up to 75 mL with distilled water. Clear aliquot of the sample and blank were pipetted and placed in an autoanalyser Technicon AAH (Pulse Instruments Ltd, Saskatoon, Saskatchewan, Canada) for the determination of total N. The percent total N was calculated as follows:

$$\%\ Total\ N = \frac{(a - b) \times 75}{weight\ of\ sample\ (g) \times 10000} \quad [3.14]$$

where:

a = N content of the soil sample b

= N content of the blank

10000 correspond to the coefficient of conversion from ppm N to percent N

75 mL = final diluted volume of digest

3.2.5. Soil available phosphorus

Soil available phosphorus was determined by the Bray No.1 method (Bray and Kurtz, 1945) as described by van Reeuwijk (1993). Four grams portion of air-dried soil (2 mm sieved) was weighed into flasks of 100 mL (two blanks and a control soil sample were included) and 14 mL of Bray No.1 solution (0.03 *M* NH_4F and 0.025 *M* HCl) were added. The mixture was then shaken for 5 min on a mechanical shaker, allowed to stand for 2 min and then centrifuged for 5 min at 3000 rpm and filtered through a Whatman N°. 42, filter paper. Five milliliters (5 mL) portion of the extract (sample) was pipetted into a volumetric flask of 25 mL followed by the addition of 4 mL of ascorbic acid solution and mixed thoroughly. The volume of the solution was made up to 25 mL with distilled water. After which the solution was allowed to stand for at least an hour for the blue colour to develop to its maximum. Standard series containing 0.1, 2, 2.4, 3.6, 4.8 and 6.0 mg L^{-1} P were also prepared and treated similarly. The absorbance was measured on the spectrophotometer (Wagtech Projects Ltd, UK) at 882 nm. The available P (mg kg^{-1} soil) was calculated as follows:

$$P\,(mg\ kg\ soil^{-1}) = (a - b) \times \frac{14}{S} \times mcf \qquad [3.15]$$

Where:

a = mg L^{-1} P in the sample extract b

= mg L^{-1} P in the blank

S = air-dry weight of the soil sample in gram mcf

= moisture factor of conversion

3.2.6. Determination of exchangeable bases

Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were extracted by the ammonium acetate (NH_4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). Five grams (5 g) portion of air-dried and sieved (2 mm) soil was weighed into extraction plastic flask and 40 mL of 1.0 *M* ammonium acetate extraction solution at pH 7 was added. The suspension was shaken for four hours on a mechanical shaker and the extract was filtered into reagent bottles through a Whatman No. 42, filter paper. One milliliter of the extracted solution was pipetted into a volumetric flask of 50 mL. Depending on the parameter to be determined in the solution, 5 mL of cesium chloride (for Na^+ and K^+) or lanthanum chloride (for Mg^{2+} and Ca^{2+}) were then added and the volume of the solution was made up to 50 mL with distilled water. Exchangeable Ca and Mg were measured by flame atomic absorption spectrophotometry (AAS) at wavelengths 422.7 and 285.2, respectively and Exchangeable K and Na by flame emission spectrophotometry (FES) at wavelengths 766.5 and 589.0, respectively. The standard series 0, 5, 10, 15, 20 and 25 mg L^{-1} and 0.1, 0.5, 1.0, 1.5, 2.0 and 2.5 mg L^{-1} were used for Ca and Mg, respectively. The standard series 0, 2.5, 5, 7.5 and 10 mg L^{-1} were used both for Na and K. The concentrations of Na^+, K^+, Ca2$^+$ and Mg^{2+} were calculated as follows:

$$Ca^{2+}\left(cmol_c\,kg^{-1}\,soil\right) = \frac{(a - b) \times 10 \times 100 \times mcf}{10 \times 20.04 \times s}$$ [3.16]

$$Mg^{2+}\left(cmol_c\,kg^{-1}\,soil\right) = \frac{(a - b) \times 10 \times 100 \times mcf}{10 \times 12.15 \times s}$$ [3.17]

$$K^{+}(cmol\ kg\ soil^{-1}) = \frac{(a-b) \times 2 \times 100}{10 \times 39.1 \times s} \times mcf \quad [3.18]$$

$$Na^{+}(cmol\ kg\ soil^{-1}) = \frac{(a-b) \times 2 \times 100}{10 \times 23.00 \times s} \times mcf \quad [3.19]$$

where:

a = mg L^{-1} of Ca, Mg, K and Na in the diluted sample

b = mg L^{-1} of Ca, Mg, K and Na in the diluted blank

s = air-dry weight of the soil sample in gram mcf = moisture factor of conversion

3.2.7. Determination of soil bulk density

Bulk density (BD) was determined by the core method (Blake and Hartge, 1986). It is expressed in kg m^{-3} as the ratio between the Mass Ms (expressed in kg) of oven dry soil (at 105 ˚C for 24 hours) and the sample volume V (m^3). The soil bulk density was calculated as follows:

$$BD\ (kg\ m^{-3}) = \frac{Ms\ (kg)}{V\ (m^3)} \quad [3.20]$$

3.2.8. Determination of particle size distribution

The particle size distribution was determined using Robinson's method as described by ICRISAT Soil and plant laboratory (2013). The pipette method is based on sedimentation of particles by gravity according to the Stoke's law. Fifty grams (50 g) portion of air-dried soil sample was transferred into a 200 mL beaker, and 50 mL of hydrogen peroxide was added and covered with a watch glass and allowed to stand overnight. On 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) and further treatment with deionized water was done as necessary. Excess hydrogen peroxide was eliminated by boiling more vigorously for 1 hour after which five drops of ammonia was added and the suspension was further boiled for another 30 minutes. The sample was transferred into a 1000 mL graduated sedimentation cylinder, and further rinsed from the beaker followed by the addition of 25 mL of pyrophosphate (or sodium hexa-metaphosphate) solution and made up to volume with distilled water.

The clay and silt (C + S) fractions were determined by mixing the content of each cylinder using a metallic rod 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 beakers of known weights. The beakers containing the pipetted suspensions were placed in an oven at 105-110 ˚C for 24 hours. The beakers were removed thereafter from the oven and immediately placed in a desiccator to cool. The cooled beaker with their contents were weighed on an analytical balance of precision 0.1 mg.

The clay (C) fraction was determined using the same steps as for fraction C + S, but with a corresponding time which was 2 hours 57 min. The suspensions were placed in beakers of known weights, dried in oven at 105-110 ˚C for 24 hours after which the beakers with the dried clay content were weighed.

Calculations:

$$Clay\,\% = \frac{((TC2 - TC1) - B) \times 10^3 \times 10^2}{V \times W} \quad [3.21]$$

Where:

TC1 = weight of empty beaker (g),

TC2 = weight of beaker + 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).

$$Clay + Silt\ \% = \frac{T\,C(+S)_2 - T\,C(+S)_1 - B}{V\,W} \times 10^3 \times 10^2 \qquad [3.22]$$

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

(%) = 100 – Clay (%) – Silt (%) where:

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

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

3.3. Analysis of plant materials

3.3.1. Determination of total phosphorus

One gram (1 g) of milled plant sample was weighed into a Kjeldahl digestion flask of 75 mL (Houba *et al.*, 1995). The samples were digested with sulphuric acid (H_2SO_4) + salicylic acid + hydrogen peroxide (H_2O_2) + selenium as described in section 3.1.4. 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. A Standard curve was developed concurrently with P concentrations ranging from 0.0, 5.0, 10.0, 15.0 and 20.0 mg P L^{-1}. The absorbance of the blank and the samples were read on the Colorimeter (Wagtech Projects Ltd, UK) at the wavelength of 650 nm. A graph of absorbance versus concentration (mg kg^{-1}) was plotted. The P concentration of the blank and unknown standards were read and the mg kg^{-1} P was obtained by interpolation of the graph plotted from which concentrations were determined. P content (μg) in 1.0 gram of the plant sample was estimated as follows:

P = C x df

P content in g per 100 g of plant sample was calculated as follows:

$$\% P = \frac{C \times df \times 100}{1000000} = \frac{C \times 1000 \times 100}{1000000} = \frac{C}{10} \quad [3.23]$$

where:

C = phosphorus concentration in 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)

1000000 = factor for converting μg to g.

3.3.2. Determination of total potassium

The total potassium content in the supernatant digest was determined using the Jenway flame photometer (Bibby Scientific Limited, Staffordshire, UK). 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 in the plant samples were calculated as follows:

K (μg) in 1 g of plant sample was estimated as follows

$$K = C \times df \quad [3.24]$$

K content in 100 g of plant sample was calculated using the following formula:

$$\% K = C \times df \times 100 = C \times 100 \times 100 = C \quad [3.24]$$

1000000 1000000 100

Where:

C = K concentration in 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), 1000000 = factor for converting µg to g.

3.3.3. Determination of lignin content

Lignin was determined using Acid Detergent Fiber (ADF) method described by Van Soest (1963). One gram (1 g) of milled dry plant material was weighed (W1) into a 250 mL Erlenmeyer flask and boiled for one hour in 100 mL cetyltrimethyl ammonium bromide solution (1 g cetyltrimethyl ammonium bromide in 100 mL of 0.5 M H_2SO_4) under continuous stirring. A drop of octan-2-ol was added as an antifoam agent. The solution was filtered over an ignited and pre-weighed sinter and washed 3-times with 50 mL of hot distilled water. The filtrate was washed with acetone until further decoloration was not observed. The filtrate was dried for 2 hours at 105 ˚C followed by the addition of about 10 mL of cool 72% H_2SO_4 (15 ˚C) to the cooled sinter and mixed with the filtrate. Draining acid was refilled and the mixture was kept for 3 hours in 72% H_2SO_4. Thereafter, the acid was filtered off under vacuum, and the residue was washed with hot distilled water until it was acid-free. The sinter was dried at 105 ˚C for 2 hours, cooled, and weighed (W2). The sinter was ignited at 500 ˚C for 2 hours, cooled, and weighed to determine ash content of the residue (W3). The percent lignin (%) was calculated as follows:

$$\%\ Lignin = \frac{(W2 - W3)}{W1} \times 100 \quad [3.25]$$

3.3.4. Determination of polyphenol content

Polyphenols content was determined using the Folin-Denis method (Anderson and Ingram, 1993). One gram portion of dried plant was weighed into 50 mL conical flasks. Then the ethanol (20 mL) was added to the sample and heated at 60 ˚C to extract the polyphenol. The extraction was repeated after the alcohol extract was decanted into another flask. After the third extraction, the volume of the extract was made up to 50 mL by adding ethanol. Standard solutions of tannic acid (with concentrations of 0, 20, 40, 80 and 100 mg tannic acid per liter) and samples were prepared and subjected to color development.

Absorbance values of the standard and sample solutions were read on the spectrophotometer (Wagtech Projects Ltd, UK) at a wavelength of 760 nm. A standard curve was obtained by plotting absorbance values against concentrations of the standard solutions and used to determine the polyphenol contents of sample solutions. The polyphenol concentration was calculated as follows:

$$Polyphenol\ (mg/kg) = graph\ reading \times sample\ dilution \times aliquot\ dilution \quad [3.26]$$

where:

$$Sample\ dilution = \frac{final\ volume}{weight\ of\ sample} = \frac{50}{1} \quad [3.27]$$

aliquot dilution = 50/1 (1 mL of initial 50 ml extract was put in a 50 mL flask and made to the 50 mL mark with ethanol. i.e. 50/1).

Chapter Four

Determinants of fertilizer micro-dosing induced yield increment of pearl millet on an acid sandy soil

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Chapter four

4. Determinants of fertilizer micro-dosing induced yield increment of pearl millet on an acid sandy soil

Abstract

Recent studies have reported the benefits of fertilizer micro-dosing in increasing crop yields in low input cropping systems. Little information, is however, available on the mechanisms underlying this effect. The objective of this study was therefore to determine the root-based mechanisms governing the growth enhancing phenomena of the fertilizer micro-dosing technology. A two-year experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Research Station in Niger. Four treatments consisting of (i) 2 g hill^{-1} of diammonium phosphate (DAP), (ii) 6 g hill^{-1} of compound fertilizer NPK, (iii), broadcasting of 200 kg ha^{-1} of compound fertilizer NPK (recommended rate) and (iv) un-fertilizer control were arranged in a randomized complete block design with four replications. On average, fertilizer micro-dosing treatments (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) achieved 86% and 79% of the grain yields recorded from broadcasting of 200 kg NPK ha^{-1}, respectively in 2013 and 2014. The leaf area index and leaf chlorophyll content significantly increased with fertilizer micro-dosing at the early stage of millet growth. At the same stage, fertilizer micro-dosing enhanced the lateral root length density in the topsoil (0-20 cm) by 72% and 40% at respective lateral distances of 25 cm and 50 cm from the centre of the hill compared with broadcast of 200 kg NPK ha^{-1}. Fertilizer micro-dosing did not significantly change soil pH in the root zone. It is concluded that the positive effect of fertilizer micro-dosing in increasing millet yield results from the better exploitation of soil nutrients due to early lateral roots proliferation within the topsoil.

Keywords: Fertilizer micro-dosing, mechanism, root growth, pH rhizosphere

4.1. Introduction

Fertilizer micro-dosing or hill placement of mineral fertilizer is a technology originally developed by the International Crops Research Institute for the Semi-Arid Tropics, Sahelian Center (ICRISAT-SC) with partners in Germany. This technology consists of the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing or few weeks after planting (Hayashi *et al.*, 2008; ICRISAT, 2009). Fertilizer micro-dosing relies on smaller quantities of placed mineral fertilizers targeting in priority the most limiting element that is phosphorus (Buerkert *et al.*, 2001).

Recent studies in Niger have shown that fertilizer micro-dosing results in a positive economic return to the use of fertilizer and improves fertilizer use efficiency (Tabo *et al.*, 2007). An earlier study by Muehlig-Versen *et al.* (2003) on phosphorus placement on an acid sandy soil in Niger, demonstrated that hill application of 3, 5 and 7 kg P ha^{-1} led to 72%, 81% and 88%, respectively of the grain yield produced by broadcasting 13 kg P ha^{-1} which is the recommended rate in Niger (Bationo and Mokwunye, 1991a; Buerkert *et al.*, 2001). In Mali, results based on a three-year study using small amount of DAP (3 to 10 kg ha^{-1}) showed that grain yields increased by 42% and 55% for sorghum and millet, respectively (Aune and Bationo, 2008). Based on the positive effects of this technology in improving crop yields and contributing food security of smallholder farmers in West Africa, fertilizer micro-dosing has been considered as a pathway to Africa’s Green Revolution (Twomlow *et al.*, 2010). This technology has, therefore, been described by Alliance for a Green Revolution in Africa (AGRA) as a major innovation to benefit a number of smallholder farmers in the Sahelian region of Africa (Bationo and Waswa, 2011).

Although, field studies have consistently confirmed the benefits of fertilizer microdozing in increasing crop yields in low input farming systems, there is, little information that elucidates the mechanisms underlying this effect. Elsewhere, a study on a calcareous soil (pH = 8.1) of China demonstrated that localized application of phosphorus and ammonium improves growth of maize seedling by stimulating root proliferation and rhizosphere acidification (Jing *et al.*, 2010). However, the earlier work on phosphorus placement reported by Rebafka *et al.* (1993) and Buerkert *et al.* (2001) which led to the fertilizer micro-dosing recommendation was conducted on an acid sandy soils (pH-KCl = 4.1 - 4.5) and no studies have so far been published to better understand the possible response of crop root growth dynamics to the localized application of small amount of mineral fertilizer. The objective of the current study was, therefore, to determine the root-based mechanisms governing the growth enhancing phenomena of the fertilizer micro-dosing technology.

4.2. Materials and methods

4.2.1 Experimental site description

The experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Station, Sadoré, Niger (13˚ 15' N and 2˚ 18' E). The climatic conditions are characterized by a uni-modal rainy season that occurs between June and September. The annual long-term (1983-2013) rainfall in Sadoré is 551 ± 110 mm (± standard deviation). The average temperature of this locality is 29 ˚C (ICRISAT climate data 2014). The soil was classified as a Psammentic Paleustalf and isohyperthermic in the USDA Soil Taxonomy and as a Luvic Arenosol by the FAO system (West *et al.*, 1984).

4.2.2. Experimental design and crop management

The trial was conducted during the 2013 and 2014 rainy seasons in a randomized complete block design with four replications. Four treatments were used in the current study as follows: (i) application of DAP (18–46–0; 2 g of fertilizer per hill), (ii) application of NPK fertilizer (15–15–15; 6 g of fertilizer per hill). These are the current fertilizer micro-dosing rates recommended in the study area (Tabo *et al.*, 2007). The rates of DAP and NPK were calculated to supply an equivalent quantity of P per hill (0.4 g P $hill^{-1}$) which is the most limiting element in the study area. (iii) Broadcasting of 200 kg ha^{-1} of compound fertilizer NPK (15-15-15) which is the blanket recommended rate of fertilizer in the study area (Hayashi *et al.*, 2008) and (iv) control (no fertilizer application). It is worthy to note that the same plots were used for the treatments in each year. Individual 5 x 6 m plots were separated by a 1 m alley and about 15 seeds of improved pearl millet variety ICMV 89305 (95 to 110 maturity days) were sown at 1 x 1 m spacing (10, 000 hills ha^{-1}). Millet stands were thinned to three plants per hill at 3 weeks after planting with subsequent three weeding events during the cropping period. Millet panicles were harvested on 10 October in 2013 and 15 September in 2014 which coincided with the harvest maturity stage. To determine grain yield and total dry matter yield, samples of straw and manually-threshed millet panicles were harvested from the central 3 m × 4 m of each plot and sun-dried, weighed and expressed in kg ha^{-1}.

4.2.3. Soil sampling and analysis

The initial soil samples were taken at the onset of the experiment before the treatments application from each plot at depths of 0-10, 10- 20 and 20-40 m. Each sample was analyzed for pH $_{H2O}$ (soil/water ratio of 1:2.5). Organic carbon was determined according to Walkley and Black's method as described by van Reeuwijk (1993), total N by the Kjeldhal method (Houba *et al.*, 1995) and available phosphorus by the Bray1 method (Van Reeuwijk, 1993). Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were determined by the ammonium acetate solution at pH 7 using the extraction method described by van Reeuwijk (1993). The ions H^+ and Al^{3+} released on exchange by an unbuffered KCl solution was determined using the method described by van Reeuwijk (1993). The particle size distribution was determined using Robinson method as described by ICRISAT Soil and plant laboratory.

4.2.4. Measurements of leaf area and chlorophyll content

Leaf area (LA) was determined using leaf length and width at tillering, stem elongation and flowering stages. At each measurement stage, two pearl millet hills randomly selected were harvested from each plot. The green leaves were taken to the laboratory for leaf length and leaf width measurements. Leaf length and width were measured with a rule and leaf area was calculated using the formula given by Ma *et al.* (2013) as follows:

$$\textit{Leaf}\ \text{area} = \text{leaf length} \times \text{maximum width} \times k \qquad [4.1]$$

where k is a shape factor with the value of 0.5 for partially unfolded leaves and 0.75 for completely unfolded leaves. The LAI was calculated as the ratio of LA to the plot area sampled.

Chlorophyll content of the leaves was measured using a SPAD (Soil-Plant Analyses Development)-502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA) at the same growth stages when LA measurements were made.

4.2.5. Determination of evapotranspiration

Daily rainfall data was recorded with a rain gauge located in the experimental field. Soil moisture was monitored weekly with a neutron probe (Didcot Instrument Company Limited, Station Road Abingdon, Oxon OX143 LD) through 2 m long access tubes installed in the middle of each plot. The access tubes were 7.5 in inner diameter. Before the measurements, the neutron probe had been calibrated in-situ using the gravimetric method as described by the manufacturer. Measurements were taken every 15 cm from 0 to 200 cm depth in all the plots. Evapotranspiration was calculated using the equation giving by Payne (1997) as follows:

$$ET \,\square\,\square\,\square R\ (dS\ D) \qquad [4.2]$$

where

ET is evapotranspiration, R is rainfall, dS is the change in soil water storage in the root zone, and D is the root zone drainage. The run-off was neglected in the water balance equation used because the slope of the experimental fields was less than 2% and also due to the sandy structure of the soil. The drainage was determined using the method developed by Klaij and Vachaud (1992) as described in Chapter 3. Water use efficiency was calculated with the formula used by Wang *et al*. (2010) as follows:

$$WUE\ (kg\ m\ m^{-1}) = \frac{Y}{ET} \qquad [4.3]$$

where Y is the millet grain yield in kg and ET is the evapotranspiration in mm.

4.2.6. Rhizosphere pH measurement

The rhizosphere soil was collected from the roots sampled at 0-20 cm during tillering, stem elongation and flowering stages for rhizosphere soil pH determination. After carefully removing roots from the soil, most of soil adhering to root surface was shaken off and the rhizosphere soil was carefully taken from the soil tightly adhering on the root surface. Measurements of pH were done immediately after sampling using a pH meter (Hanna Instruments Ltd, Carrollton, Taxas).

4.2.7. Root sampling and determination of root length density

In 2013, two millet hills were tagged from each plot and roots were collected on each plant sampling date (tillering, stem elongation and flowering stages) with a metal frame measuring 15 x 10 x 10 cm from 0 to 20 cm directly under the hill. Roots were subsequently collected at 20 cm depth increment with an access tube of 7.5 cm inner diameter following the first sampling depth of 0-20 cm. All roots samples were washed, debris and died roots removed. The root length was calculated by determining root intersections (N) using the line intersection method (Tennant, 1975). A grid size of 2 x 2 cm was used for coarse roots and a grid size of 1 x 1 cm for fine roots. Coarse roots were counted on a sub-sample of 2 g taken from the main root sample. For fine roots, if the fresh weight of the total sample was more than 1 g, a sub-sample weight of 1 g was taken for the count. Samples were cut into small pieces of 1 cm and spread in the dish with a small amount of water. Root length was calculated using the following formula:

$$R = \frac{N \times total\,root\,fresh\,weight}{Root\,weight\,of\,sub-sample} \qquad [4.4]$$

where N is number of intersections counted. Root length density (RLD) was determined by the following formula:

$$RLD\,(cm\,cm^{-3}) = \frac{R}{V} \qquad [4.5]$$

where R is Root length and V is soil volume of corresponding depth.

In 2014, roots were sampled at three positions, directly under the hill and at two lateral distances (25 and 50 cm) relative to the hill in four directions. After washing and removing the dead roots and debris, all the roots samples collected were scanned with 200 dpi resolution. Root images were analysed using WinRhizo Pro software (Regent Instruments Canada Inc.) to calculate root length and then root length density (RLD) was calculated from the root length and the soil core volume.

4.2.8. Statistical analysis

Prior to analysis, the data were checked for normal distribution using residual plots in GENSTAT v.9 (Trust, 2007). Root length density data were square root transformed before analysis of variance to ensure normal distribution of residuals. However, the untransformed data were presented in the manuscript. All the data collected were subjected to analysis of variance in GENSTAT v.9 using a General Treatment Structure (in Randomized Blocks). Model of ANOVA included treatments, year and their interactions. Means were compared between treatments using least significant difference (LSD) method at the 5% probability level.

4.3. Results

4.3.1. Soil physical and chemical properties

Table 4.1 presents the physical and chemical properties of soil of the experimental field. The soil was typically sandy and very strongly acid (pH_{H2O} = 5). The soil organic carbon ranged from 0.26% to 0.19% at 10 cm and 20 cm depth, respectively. The total nitrogen and available P contents were very low and decreased with depth. The available P content was less than the critical level (8 mg kg^{-1}) required to achieve 90% of maximum millet yield in the sandy soils of Niger (Manu *et al.*, 1991).

Table: 4. 1. Initial soil physical and chemical properties

	Depth (cm)	
Parameters	10	20

Soil texture (%) Sand	94.6 ± 0.2	94.7 ± 0.2
Silt	2.4 ± 0.1	2.0 ± 0.04
Clay	3.0 ± 0.2	3.3 ± 0.2
Soil chemical properties pH-H_2O (1:2.5)	5.4 ± 0.04	5.3 ± 0.01
Total-N (mg kg^{-1})	231.2 ± 8.1	159.4 ± 5.2
P-Bray 1 (mg kg^{-1})	3.3 ± 0.2	2.4 ± 0.1
Organic carbon (%)	0.26 ± 0.01	0.19 ± 0.04
Exchangeable bases ($cmol_c$ kg^{-1})	2.0 ± 0.1	1.7 ± 0.1

± Standard error

4.3.2. Rainfall distribution during the cropping periods

The rainfall distribution during the cropping period in 2013 and 2014 is illustrated in Figure 4.1. The total rainfall recorded during 2013 cropping period was 481 mm, which was less than the long-term (1983-2014) rainfall average of 551 mm yr^{-1} at the experimental site (ICRISAT, climatic database 2014). Most of the rain events occurred during August (from 40 to 65 days after sowing) which accounted for 75% of the total rainfall recorded during 2013 cropping period. There was, a dry spell of 27 days in September-October 2013, which coincided with the flowering and grain filling stages. In 2014, rainfall was evenly distributed with 689 mm recorded through the cropping period in comparison to 2013.

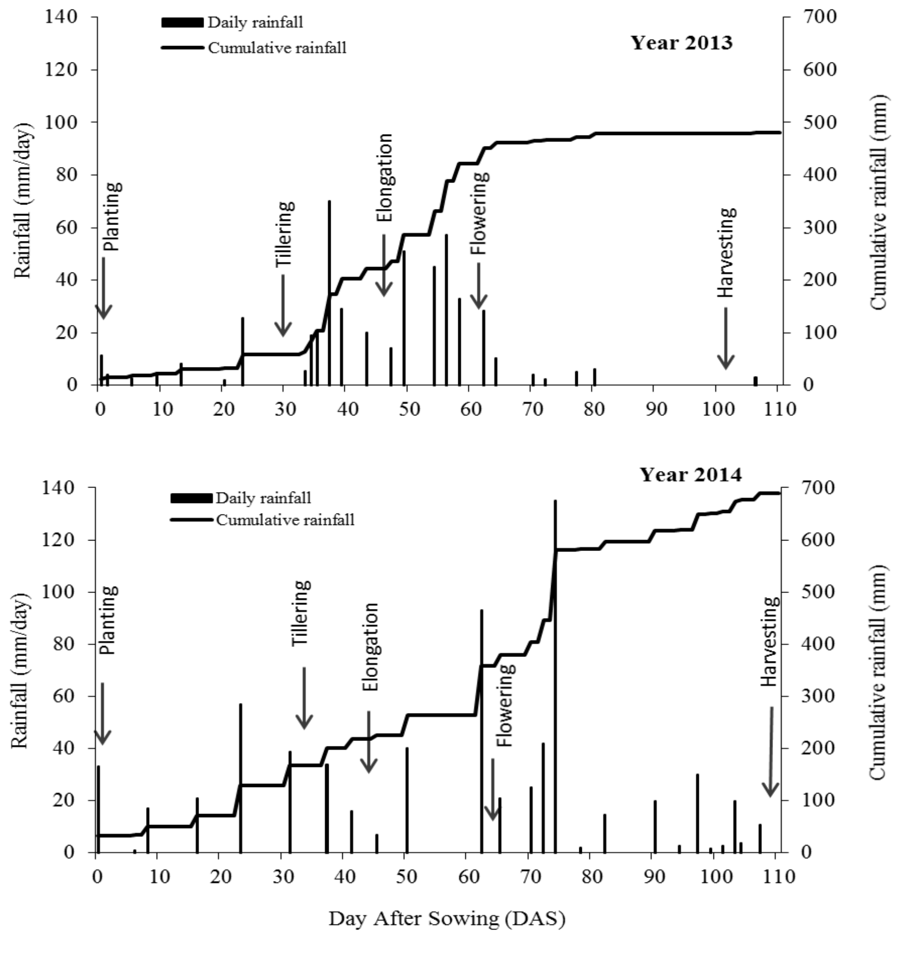


Figure 4.1. Rainfall distribution in 2013 (upper panel) and 2014 (lower panel)

4.3.3. Effect of fertilizer application methods on grain and total dry matter

Grain yields were significantly affected by the treatments and the cropping year (Table 4.2). However, no significant year by treatments interactions were found. Grain yields were significantly higher in 2014 in comparison with 2013 cropping season. Highest grain yields were recorded for broadcast of 200 kg NPK ha^{-1}. However, these grain yields were not significantly different from the 2 g DAP hill^{-1} treatment. On average, both fertilizer micro-dosing treatments (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) achieved 86% and 79% of the grain yields recorded from broadcasting of 200 kg NPK ha^{-1}, respectively in 2013 and 2014. The lowest grain yields (402 ± 18 kg ha^{-1} and 618 ± 115 kg ha^{1} in 2013 and 2014, respectively) were obtained from the un-fertilizer control plots. Similarly, the total dry matter (TDM) production was significantly affected by the treatments and cropping year (Table 4.2). However, no year by treatments interactions in TDM were detected. The total dry matter (TDM) yields recorded in both fertilizer micro-dosing plots accounted for 95% and 84% of those recorded with broadcasting of 200 kg NPK ha^{-1} in 2013 and 2014, respectively. The unfertilized control treatment produced the lowest total dry matter yield. Table: 4.2. Millet grain and total dry matter (TDM) yields

	Grain Yields (kg ha^{-1})		Total dry matter (kg ha^{-1})	
	2013	2014	2013	2014
Broadcast 200 kg NPK ha^{-1}	812 ± 57	1243 ± 79	3290 ± 166	4204 ± 343
2 g DAP hill^{-1}	780 ± 24	1039 ± 74	3216 ± 157	3750 ± 301
6 g NPK hill^{-1}	611 ± 46	921 ± 139	3030 ± 176	3306 ± 293
Control	402 ± 18	618 ± 115	1605 ± 171	2667 ± 301
F.pr				
Year	< 0.001		< 0.001	
Treatments	< 0.001		< 0.001	
Year x Treatments	0.157		0.053	
Lsd (0.05)				
Year	70		209	
Treatments	99		296	
Year x Treatments	140		418	

± Standard error of means

4.3.4. Evapotranspiration (ET) and water use efficiency (WUE)

Evapotranspiration (ET) and water use efficiency in grain were presented in Table 4.3. ET was significantly higher in 2014 cropping season compared with 2013 cropping season. There was, however, no significant differences in ET among the treatments. WUE in grain was significantly affected by the treatments. Broadcast of 200 kg NPK ha^{-1} and micro-dosing of 2 g DAP hill^{-1} were more efficient in using water than the other treatments. In fact, the plots receiving fertilizer micro-dosing treatments recorded

93% and 83% of the water use efficiency in grain yields achieved by broadcasting of 200 kg NPK ha^{-1} plots in 2013 and 2014, respectively. There were, no significant year by treatment interactions in grain water use efficiency (Table 4.3).

Table: 4.3. Evapotranspiration (ET) and water use efficiency (WUE)

	Evapotranspiration (mm)		Grain WUE (mm kg^{-1})	
	2013	2014	2013	2014
Broadcast 200 kg NPK ha^{-1}	291 ± 27	304 ± 9	2.8 ± 0.2	4.1 ± 0.2
2 g DAP hill^{-1}	267 ± 17	292 ± 8	2.9 ± 0.1	3.6 ± 0.3
6 g NPK hill^{-1}	263 ± 15	292 ± 6	2.3 ± 0.1	3.2 ± 0.4
Control	276 ± 24	293 ± 9	1.5 ± 0.1	2.1 ± 0.5
F.pr				
Year	0.046		< 0.001	
Treatments	0.460		< 0.001	
Year x Treatments	0.917		0.525	
Lsd (0.05)				
Year	20		0.6	
Treatments	29		0.8	
Year x Treatments	40		1.2	

± Standard error of means

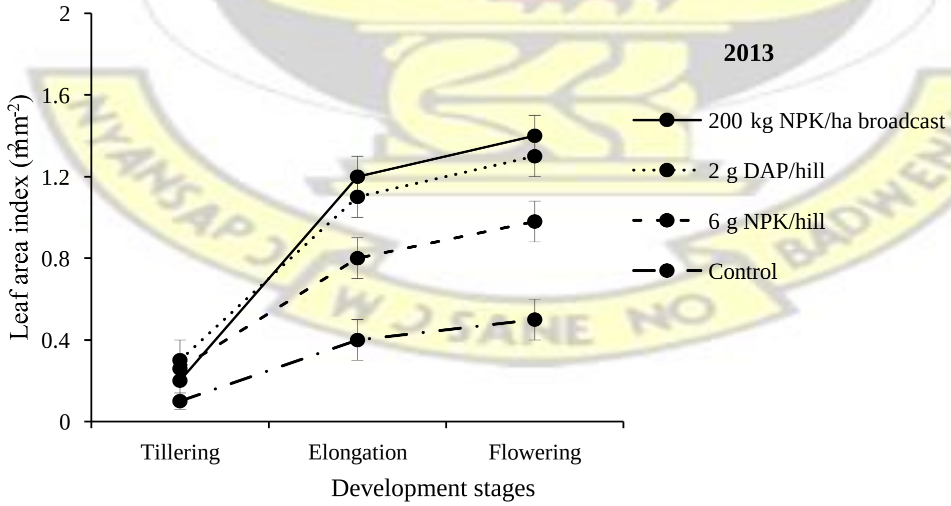
4.3.5. Effect of fertilizer application methods on millet growth parameters

Leaf chlorophyll concentration was significantly different among the treatments at different millet growing stages (Table 4.4). Chlorophyll concentration was highest with the micro-dosing treatment (2 g DAP hill^{-1}) at tillering and stem elongation stages with 32 and 36 SPAD units and 33 and 44 SPAD units in 2013 and 2014, respectively. However, there was, no significant difference in leaf chlorophyll concentration at tillering between treatment receiving the broadcast of 200 kg NPK ha^{-1} and the fertilizer micro-dosing treatments. At the stem elongation and flowering stage, application of 6 g NPK hill^{-1} had significantly lower leaf chlorophyll content than those of the broadcast of 200 kg NPK ha^{-1} and 2 g DAP hill^{-1} treatments. During flowering stage, the highest chlorophyll concentration (41 SPAD units) was obtained from the broadcast of 200 kg NPK ha^{-1} in 2013. The variation in leaf area index (LAI) (Figure 4.2), followed the same trend as that of the chlorophyll concentration. The LAI was significantly different among the treatments and peaked at flowering stage with the highest value of 1.4 and 1.8 recorded from broadcast of 200 kg NPK ha^{-1} treatment in 2013 and 2014, respectively. However, these values were not significantly different from those of 2 g DAP hill^{-1}.

Table: 4.4. Chlorophyll content at different development stages of millet

	2013			2014		
	Till	Elon	Flo	Till	Elon	Flo
200 kg NPK ha $^{-1}$ broadcast	26^{ab}	34^{a}	41^{a}	28^{b}	40^{a}	52^{a}
2 g DAP hill^{-1}	32^{a}	36^{a}	39 ^{a}	33^{a}	44^{a}	57^{a}
6 g NPK hill^{-1}	27^{ab}	33^{b}	36^{a}	30^{a}	36^{b}	46^{b}
Control	22^{b}	24^{c}	24 ^{b}	25^{b}	33^{b}	42^{b}
F pr	0.043	< 0.001	0.004	0.039	0.043	0.035
CV (%)	12	13.2	9.2	6.4	9	9
Lsd (0.05)	6.4	2	6.5	4.2	6.9	9

Means within a column followed with the same letters are not significantly different at $P < 0.05$. Till = tillering; Elon = Elongation; Flo = Flowering



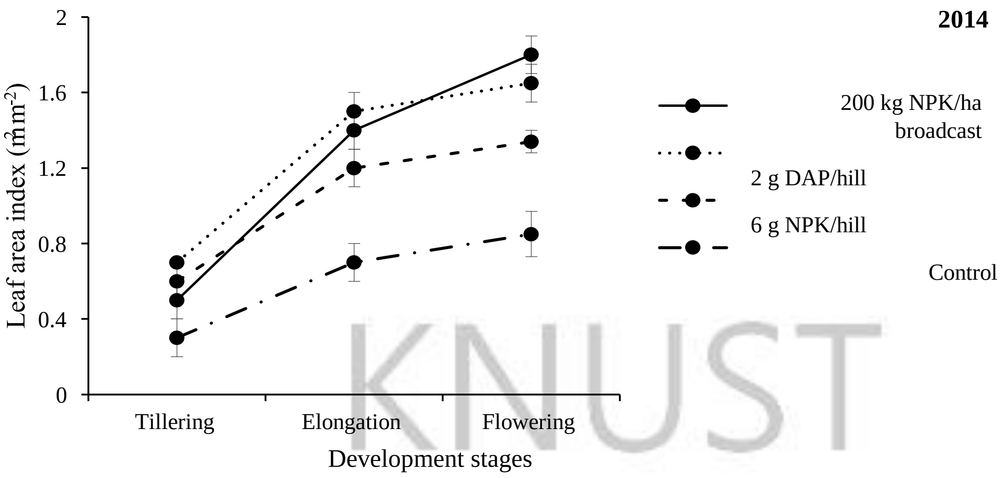


Figure : 4.2. Leaf area index at different development stages of millet

4.3.6. Effect of fertilizer application methods on rhizosphere pH

There was, a rapid change in rhizosphere pH at tillering stage with fertilizer microdosing treatments compared to the broadcast of 200 kg NPK ha^{-1} (Table 4.5). However, this change was not significant. At flowering growth stage, a decrease of rhizosphere pH by 0.4 units was recorded for broadcast of 200 kg NPK ha^{-1} in comparison with the rhizosphere pH level at tillering stage. The decrease in rhizosphere pH was less marked with fertilizer micro-dosing treatment (6 g NPK hill^{-1}) and the control treatments. There were, however, no significant differences in rhizosphere pH among the treatments at different developmental stages of millet (Table 4.5).

Table: 4.5. Rhizosphere pH at different developmental stages of millet

	Developmental stages		
Treatments	Tillering	Elongation	Flowering
200 kg NPK ha^{-1} broadcast	5.4 ± 0.1	5.1 ± 0.1	5.0 ± 0.1
2 g DAP hill^{-1}	5.6 ± 0.1	5.2 ± 0.1	5.1 ± 0.04
6 g NPK hill^{-1}	5.5 ± 0.1	5.2 ± 0.03	5.2 ± 0.01
Control	5.4 ± 0.1	5.4 ± 0.01	5.3 ± 0.1

F.pr	0.509	0.186	0.065
Lsd (0.05)	0.4	0.3	0.2
CV (%)	13.9	12.6	12.3

± Standard error

4.3.7. Root length density dynamics in response to fertilizer placement

Nutrient addition improved root growth at all the stages of millet development (Figure 4.3). At tillering stage, topsoil (0-20 cm) root length density (RLD) of millet was higher in the fertilizer micro-dosing treatments while in deeper soil layers, RLD was highest for broadcasting of 200 kg NPK ha^{-1} plots. However, at node formation this gap was narrowed for broadcasting of 200 kg NPK ha^{-1}. Nevertheless, at flowering stage micro-dosing with 2 g DAP $hill^{-1}$ and broadcasting of 200 kg NPK ha^{-1} resulted in similarly higher RLD in the topsoil (0-20 cm) while at deeper soil layers, RLD was still higher for the broadcasting of 200 kg NPK ha^{-1}. Lateral root length density in the topsoil (0-20 cm) was significantly increased by 72% and 40% with fertilizer microdosing treatments at the lateral distances 25 cm and 50 cm, respectively from the centre of the hill compared with broadcast of 200 kg NPK ha^{-1} (Figure 4.4). In all treatments, overall RLD decreased with increasing soil depth. However, this decrease in RLD was less drastic in broadcast of 200 kg NPK ha^{-1} than in fertilizer micro-dosing treatments where the roots were mostly concentrated in nutrient-rich patches.

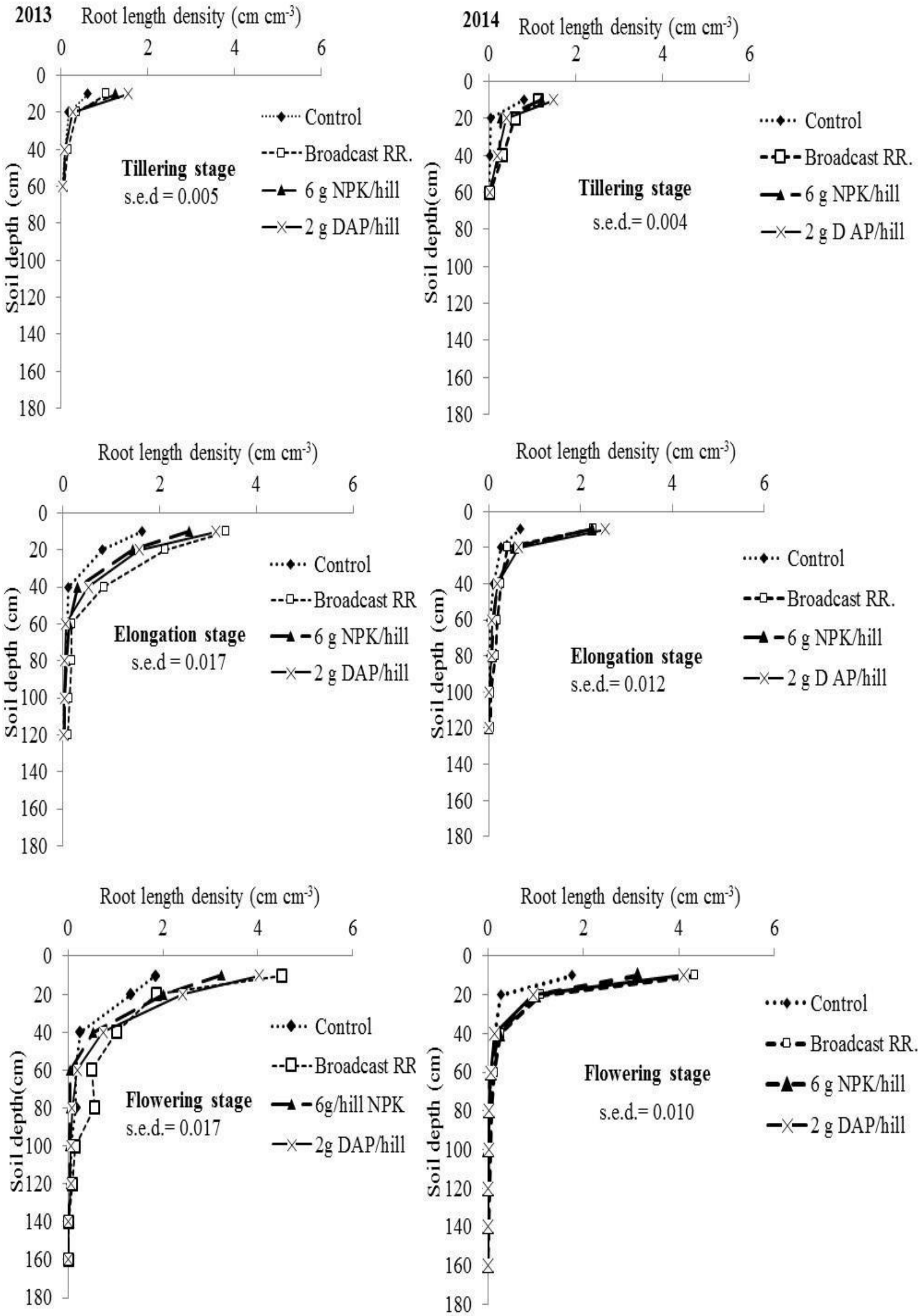


Figure: 4.3. Vertical root length density of hill planted pearl millet

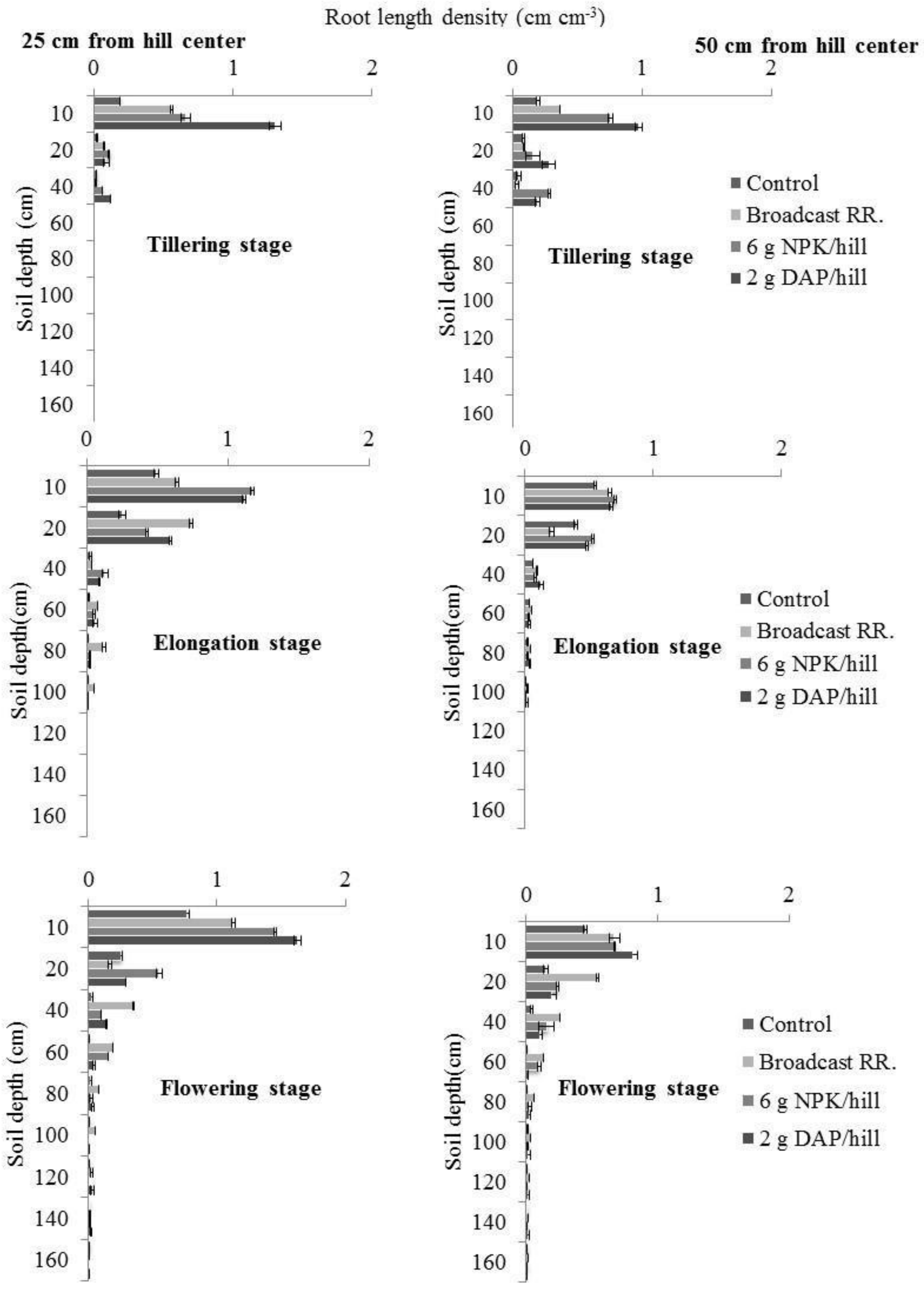


Figure: 4.4. Root length density of pearl millet in 2014 at 25 cm and 50 cm lateral distances from the hill. Error bars denote standard error.

4.4. Discussion

The increase in millet yields observed in this study was in line with the results of other recent studies on fertilizer micro-dosing in West Africa (Hayashi *et al.*, 2008; Tabo *et al.*, 2011; Ibrahim *et al.*, 2014) . The response of pearl millet to minute application rates of mineral fertilizer in Sahelian sandy soils can be explained by the low inherent fertility which leads to the positive responses following any improved soil fertility management practice.

Millet grain yields and total dry matter production were significantly affected by the cropping seasons. The yields were significantly higher in 2014 cropping season than the 2013 cropping season (Table 4.2). Earlier research reported the residual effect of mineral fertilizer particularly P fertilizer in increasing productivity of the subsequent crop in Niger (Bationo *et al.*, 1992). It, is however, unlikely that the large differences in yields obtained in the current study could be due to the residual effect of fertilizer because, for instance, with the small quantity of P applied (4 kg ha^{-1}), a minimal residual effect could be expected. Moreover, no residual effects of P placement at 5 to 7 kg ha^{-1} were detected in the dry matter yields, two years after the last addition of SSP to millet plots on a Luvic Arenosol in the Sahelian zone of Niger (Gérard *et al.*, 2001). Rather, higher yields obtained in 2014 could be attributed to the larger amount and better distribution of rainfall observed throughout the growing period in 2014 (Figure 4.1) which translated into higher millet growth and biomass production. The inter-annual yield differences as a result of rainfall variability have been extensively reported in the Sahel (Sivakumar and Salaam, 1999; Akponikpé *et al.*, 2008; Ibrahim *et al.*, 2015).

Millet response to fertilizer micro-dosing depends on the type of fertilizer applied.

In general, increases in yields were higher with DAP than with NPK compound fertilizer (Table 4.2). The same conclusion was also reached by Bielders and Gérard (2014). It seems possible that the higher grain yield obtained with DAP was due to its ability to increase the soil pH in the immediate vicinity of the roots i.e., the rhizosphere upon dissolution (Black *et al.*, 1985; Fan and Mackenzie, 1993). The change in rhizosphere pH at the early stage of crop growth increases soil nutrients availability such as extractable P, Ca and Mg close to roots zone (Bagayoko *et al.*, 2000). However, this increase in pH with DAP may not persist for longer period (Khasawneh *et al.*, 1980) as the pH drops with the transformations of ammonium to nitrate. The early season (millet tillering stage) increase in rhizophere pH recorded in this study followed by a decrease of pH at flowering stage (0.4 units) cannot be attributed merely to the effect of the type of fertilizer applied since the same situation was observed in the other treatments (Table 4.5). The decrease in rhizophere pH can be attributable to the poorly pH buffering capacity of the soil due to low soil organic matter content (Hinsinger *et al.*, 2003) which is the case of this experimental sandy soil characterizing by very low soil organic matter content (Table 4.1). There is, however, another plausible explanation which is related to the leaching of ions such as nitrate leading to a loss of ionic balance in soil solution (Rengel *et al.*, 2000; Weligama *et al.*, 2008; Russo *et al.*, 2014).

The effect of fertilizer micro-dosing in improving crop yields has been attributed largely to the early crop development (Tabo *et al.*, 2007). This is consistent with the finding in the current study that provides an empirical evidence of the increase in leave chlorophyll concentration under fertilizer micro-dosing treatments (2 g DAP hill^{-1} and 6 g NPK^{-1}) at tillering stage leading to an increased production of photosyntates for enhanced leaf area development and biomass production (Table 4.4 & Figure 4.2).

There was, a significant difference in water use efficiency between the treatments (Table 4.3). Broadcast of 200 kg NPK ha^{-1} and micro-dosing of 2 g DAP $hill^{-1}$ were more efficient in using water as a result of highest yields obtained in these treatments. These results are in close agreement with the earlier studies which reported an increment of millet water use efficiency in response to soil fertility management options in the Sahelian zone due to increase in biomass production (Payne, 1997; Yamoah *et al.*, 2002). Moreover, Viets (1962) explained that since the evapotranspiration is little affected by the management, as was the case in the current study (Table 4.3), any factor that increases yield will increase WUE. The small differences observed in evapotranspiration among the treatments could be explained by the fact that under dry climatic conditions and sandy soils in Niger, practically all the plant available water (PAW) is used by the crop and since evapotranspiration losses are largely controlled by meteorological conditions, seasonal ET is almost the same whether yields are high or low (Sivakumar and Salaam, 1999).

Rapid root growth and desired architecture development play an important role in nutrients and water acquisition by the plants in low soil fertility and dry environments (Brück *et al.*, 2003; Vadez *et al.*, 2007). Root length density (RLD) in this study was mostly concentrated in the topsoil (0-20 cm) and drastically declined within the lower soil depths. This decrease in RLD can likely be attributed to the progressively lower pH of the soil in the experimental field (Table 4.1) that probably limited root development (Marschner, 1991). In the current study, the millet roots under fertilizer micro-dosing treatments did not penetrate deeper soil layers to scavenge for nutrients and water as compared to the broadcast of mineral fertilizer (Figure 4.3). The concentration of millet roots in the topsoil with fertilizer micro-dosing was in line with the crop response to the localised application of nutrients leading to roots proliferation in patches with high nutrient concentration (Hodge, 2004). It has been postulated that the reason of fertilizer micro-dosing inducing higher crop yields was due to the positive effect of this technology in stimulating root growth in deeper soil layers and therefore enhancing crop nutrient and water uptake (Aune and Bationo, 2008). In the sandy soil such as in this case with shallow soil depth where most of the nutrients are concentrated in the topsoil, the lateral proliferation of the roots within the upper soil layer can be of immense benefit to the crops. The increase in lateral root length density at early millet growth with fertilizer micro-dosing (Figure 4.4) could subsequently stimulate uptake of native P because of the particularly high uptake capacity of young roots for this nutrient (Ma *et al.*, 2013; Smit *et al.*, 2013). This sequence is a plausible explanation for the positive effect of fertilizer micro-dosing in increasing millet yields on the acid sandy soil. However, in drought prone areas, the extraction of water accumulated in the deeper soil layers is of utmost importance for a crop to cope with the recurrent dry spells throughout the cropping period. The development of a deep rooting system is therefore important for improving further nutrients and water use by the crop. This was not however, the case with fertilizer micro-dosing because the results on water use obtained in this study showed that fertilizer micro-dosing could not improve plant water use (Table 4.3). It, therefore, becomes necessary to supplement fertilizer micro-dosing with organic amendments in order to promote rapid and deep root growth. Further experimental work deserves therefore being undertaken to establish the potential effects of combined use of fertilizer micro-dosing and organic amendment on root growth and water use.

4.5. Conclusion

The results of the current study indicated that millet roots under fertilizer micro-dosing treatments did not penetrate deeper soil layers to scavenge for nutrients and water as compared to the broadcast of mineral fertilizer. At the early stage of millet growth, the lateral root length density in the topsoil (0-20 cm) was significantly increased by 72% and 40% with fertilizer micro-dosing treatments at the lateral distances 25 cm and 50 cm, respectively from the centre of the hill compared with broadcast of 200 kg NPK ha^{-1}. It is concluded that the positive effect of fertilizer micro-dosing in increasing millet yield results from the better exploitation of soil nutrients due to early lateral roots proliferation within the topsoil.

Chapter Five

Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system

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Chapter Five

5. Hill placement of manure and fertilizer microdosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system

Abstract

Inadequate nutrient supply and insufficient rainfall are the most important limiting factors for crop production in the Sahelian agro-ecological zones. Targeted technology application may help to improve the efficient use of limited nutrient and water resources. The objective of this study was to determine the optimal combination of fertilizer micro-dosing and manure application rates for improved millet yield and enhanced water use efficiency in low input millet-based cropping system. A two-year field experiment was conducted at a Research Station in Niger using a randomized complete block design with three replications. The treatments consisted of the factorial combination of: (i) two fertilizer micro-dosing options (20 kg ha^{-1} of diammonium phosphate (DAP) and 60 kg ha^{-1} of NPK corresponding to 2g hill^{-1} of DAP and 6g hill^{-1} of NPK, respectively), (ii) cattle manure at 4 application rates (0 kg ha^{-1} 1000 kg ha^{1}, 2000 kg ha^{-1}, 3000 kg ha^{-1}) and (iii) two methods of manure application (broadcasting and hill placement). Millet grain yields under fertilizer micro-dosing combined with manure was increased on average by 59%, 83% and 113% for 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}, respectively compared with fertilizer micro-dosing alone. Combined application of manure and fertilizer micro-dosing increased water use efficiency significantly. Hill placement of manure increased total dry matter on average by 23% and water use efficiency by 35% relative to manure broadcasting. The total root length density was increased by 66% and 42% in hill placement of manure at 25 cm and 50 cm, respectively, from the hill centre compared with manure broadcast. These results indicate that millet production with the fertilizer micro-dosing technology can be improved further by hill-placement of manure. The combination of 2000 kg ha^{-1} of manure and 20 kg DAP ha^{-1} hill-placed were most promising for increasing millet yield and the efficient use of limited water in Sahelian millet-based

cropping system. There is, need for testing this technology further together with farmers to valuate its effectiveness.

Keywords: millet, fertilizer micro-dosing, manure, hill-placement, yield, water use efficiency

5.1. Introduction

Pearl millet is the major food cereal cultivated in the Sahelian agro-ecological zone of Niger on coarser textured soils using up to 90% of the cropped area (Bationo *et al.*, 1993). Even though this crop has a potential to adapt to harsh conditions, particularly low soil fertility, its yield is often very low with an average of 400 kg ha^{-1} in low input smallholder millet farming systems (Sivakumar and Salaam, 1999). The inherent low soil fertility coupled with inappropriate soil fertility management and unreliable rainfall are main causes underlying the low millet productivity in the Sahelian zone of Niger (Stoorvogel and Smaling, 1990; Graef and Haigis, 2001; Schlecht *et al.*, 2006).

The use of mineral fertilizers by farmers in Niger remains very low and unattractive because of their high cost (Bationo *et al.*, 2003; Abdoulaye and Sanders, 2005). To improve the efficient use and to encourage smallholder farmers to increase the on-farm application of mineral fertilizer, the fertilizer micro-dosing technology developed by ICRISAT and partners has shown promising results in improving millet yields in the Sahel (Tabo *et al.*, 2007; Aune and Bationo, 2008). This technology consists of the application of a small quantity of mineral fertilizer (one third of the recommended rate) to the target crop seeds on the planting hill at the sowing event or few weeks after planting (Hayashi *et al.*, 2008; ICRISAT, 2009). However, in recent works on millet response to fertilizer micro-dosing technology, it was indicated that low soil organic matter characterizing the Sahelian sandy soils contributes immensely to the low millet yield response to this technology (Manyame, 2006; Tabo *et al.*, 2011). Therefore, it appears that to enhance crop response to fertilizer micro-dosing technology, there is, a need to supplement it with an organic resource.

The effectiveness of integrated use of mineral and organic amendment in improving crop yields and maintaining (sustainably) soil fertility has been well documented (Yamoah *et al.*, 2002; Bationo *et al.*, 2003; Akponikpé *et al.*, 2008), but the availability of the resources for achieving these positive effects remains a major challenge, especially in the Sahelian countries. The main sources of organic amendments such as crop residue are used for other purposes and thereby limit their availability for use as soil amendment (Bationo *et al.*, 1995). Animal manure is the most common organic resource for smallholder farmers but its availability in sufficient quantity is also a major challenge (de Ridder and Van Keulen, 1990; McIntire *et al.*, 1993). One of the available options for addressing this problem could be through hill placement of manure which could be a strategy for increasing millet productivity when combined with fertilizer micro-dosing. The objective of the current study was, therefore, to determine the combination of fertilizer micro-dosing and manure applications for achieving high millet yields, and water use efficiencies in low input millet-based cropping system.

5.2. Materials and methods

5.2.1. Description of experimental site

The experiment was carried out at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Station, Sadoré, Niger (13˚ 15’ N and 2˚ 18’ E, 240 m above sea level). The climate is typical of the southern edge of the Sahelian zone, with rainfall and high temperature throughout the year (Sivakumar *et al.*, 1993).

The mean annual rainfall (1983-2014) at the Research Station of Sadoré is 551 ± 110 mm (± standard deviation) and the average temperature is 29°C (ICRISAT climate database). The experimental field had a sandy soil with low organic carbon content (0.20% in the upper 40 cm of soil) which limits nutrients storage and water holding ability. The total nitrogen (N) content and available phosphorus (P-Bray) contents were also relatively low at 205 mg kg^{-1} and 7.9 mg kg^{-1}, respectively, soil pH (H_2O) was about 5 (Table 5.1).

5.2.2. Experimental set up

The experiment was conducted during the rainy season in 2013 and 2014 in a randomized complete block design with three replications. The treatments consisted of factorial combinations of (i) two fertilizer micro-dosing options: 20 kg ha^{-1} of diammonium phosphate (DAP) (equivalent to 4 kg P ha^{-1} and 3.6 kg N ha^{-1}) and 60 kg ha^{-1} of composite fertilizer NPK 15-15-15 (equivalent to 4 kg P ha^{-1}, 9 kg N ha^{-1} and 7.47 kg K ha^{-1}). The micro-dosing rates correspond to 2 g DAP hill^{-1}and 6 g NPK hill^{1}, respectively. (ii) Cattle manure with 4 application rates (0 kg ha^{-1}, 1000 kg ha^{-1}, 2000 kg ha^{-1}, 3000 kg ha^{-1}) and (iii) two methods of manure application (broadcasting and hill placement). Individual 5 m x 6 m plots were separated by a 1 m alley. The space between the planting hills was 1 x 1 m to achieve a density of 10,000 hills ha^{-1} as recommended in Niger. In the plots receiving broadcasted manure, 3 kg plot^{-1}, 6 kg plot^{-1} and 9 kg of manure plot^{-1} corresponding to 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}, respectively were broadcast over the plots and superficially incorporated into the soil with a long hand-led hoe known as a "*hiliaire*". For manure hill placement, small planting hills of 15 cm diameter and 15 cm depth each were dug in the experimental plots and 100 g hill^{-1}, 200 g hill^{-1} and 300 g of manure hill^{-1} were applied, which represented 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}, respectively. About 15 seeds of improved pearl millet variety ICMV-IS 89305 (110 maturity days) were sown at the onset of the rainy season on 10th July, 2013 and 1st June, 2014. The plants were thinned to three plants per hill at three weeks after planting. There were three weeding events during the growing period. The harvest periods occurred on 10th October in 2013 and 15th September in 2014. To determine grain yield and dry matter yield, samples of straw and manually-threshed millet panicles were harvested from the central 4 m x 5 m of each plot and sun-dried, weighed and expressed in kg ha^{-1}.

Table: 5. 1. Initial soil chemical and physical properties of the experimental field

Parameters	0-10 cm	10-20 cm	20-40cm
Soil texture			
Sand (%)	94.1	95.0	92.1
Silt (%)	3.9	2.2	2.1
Clay (%)	2.0	2.8	5.4
Soil chemical properties pH-H_2O (1:2.5)	5.1	4.9	4.7
pH-KCl (1:2.5)	4.8	4.1	3.9
Organic C (%)	0.31	0.15	0.13
Total N (mg kg^{-1})	311	170	135
Available P (mg kg^{-1})	8.9	7.7	7.2
Ammonium (mg kg^{-1})	8.8	5.5	3.7
Nitrate (mg kg^{-1})	19.3	11.7	5.9
Exchangeable Na (cmol$_c$ kg^{-1})	0.01	0.01	0.01
Exchangeable K (cmol$_c$ kg^{-1})	0.17	0.16	0.17
Exchangeable Ca (cmol$_c$ kg^{-1})	1.0	1.3	0.8
Exchangeable Mg (cmol$_c$ kg^{-1})	0.4	0.6	0.3
Exchangeable H (cmol$_c$ kg^{-1})	0.1	0.1	0.2
Exchangeable Al (cmol$_c$ kg^{-1})	0.0	0.2	0.3

5.2.3. Soil sampling and analysis

Composite soil samples were taken before the treatments were applied, at depths of 010, 10-20 cm and 20-40 cm. Each sample was analyzed for pH-H_2O and pH-KCl (soil: solution ratio of 1:2.5). Organic carbon was determined with the Walkley and

Black's method as described by van Reeuwijk (1993), total N by Kjeldahl method (Houba *et al.*, 1995) and available phosphorus by the Bray 1 method (van Reeuwijk, 1993). Exchangeable bases (Na^{+}, K^{+}, Ca^{2+} and Mg^{2+}) were determined by the ammonium acetate solution at pH 7 using the extraction method described by van Reeuwijk (1993). The particle size distribution was determined using Robinson method as described by ICRISAT Soil and plant laboratory. The details of laboratory protocols for the soil chemical and physical proprieties were provided in Chapter 3.

5.2.4. Root sampling and root length determination

In 2013, two millet hills from each treatment were sampled and roots were collected at tillering and dough stages with a metal frame measuring 15 x 10 x 10 cm from 0 to 20 cm directly under the hill. Roots were subsequently collected at 20 cm depth increment with an aluminium tube of 7.5 cm diameter following the first sampling depth of 0-20 cm. The roots were washed, and debris and dead roots removed. The root length was calculated by determining root intersections (N) using the grid counting method (Tennant, 1975). In 2014, two millet hills from each treatment were tagged and roots were sampled in three positions, directly under the hill and at two lateral distances (25 cm and 50 cm) relative to the hill in four directions at tillering and dough stages. After washing and removing dead roots and debris, all the roots samples collected were scanned through a scanner with 200 dpi resolution. The root length and root length density were determined as described in section 4.2.7.

5.2.5. Soil moisture monitoring and water use efficiency calculation

The rainfall data were recorded with a rain gauge located at the experimental field. Access tubes were installed in all the plots to monitor weekly soil moisture with a calibrated neutron probe from 15 cm to 200 cm depth at 15 cm intervals. The evapotranspiration was derived from water balance equation used by Payne (1997) as follows:

$$\Delta S = R - (ET + D) \quad [5.1]$$

where ΔS is the change in soil water storage in the root zone, ET is evapotranspiration, R is rainfall, and D is the root zone drainage. The drainage was determined using the method developed by Klaij and Vachaud (1992). Water use efficiency (kg mm^{-1}) was calculated as a ratio of grain yield or total dry matter (TDM) to evapotranspiration (Wang *et al.*, 2010).

5.2.6. Statistical analysis

Prior to the analysis, data were carefully checked for normal distribution in GENSTAT v.9 using Distributions options. Square root (Sqrt) transformation was applied to root length density data only to ensure normal distribution because the residual failed to satisfy this assumption of analysis of variance. The analysis of variance was, therefore, performed with GENSTAT v.9 (Lawes Agricultural Trust, 2007) using a General Treatment Structure (in Randomized Blocks). Differences among treatments were considered at error probabilities ≤ 0.05.

5.3. Results

5.3.1. Rainfall distribution during the cropping period

Figure 5.1 shows the total rainfall recorded during the cropping period in 2013 and 2014. The total rainfall recorded was 475 mm and 689 mm in 2013 and 2014, respectively. In 2013, the rainfall was about 76 mm less than the long-term rainfall (551 mm) recorded in the experimental site (ICRISAT Climate Service) and it was mostly concentrated between 20 to 68 days after sowing DAS), corresponding to the flowering stage. A long dry spell of 25 days occurred coinciding with millet reproductive stage period. The rainfall was more evenly distributed in 2014 compared with 2013.

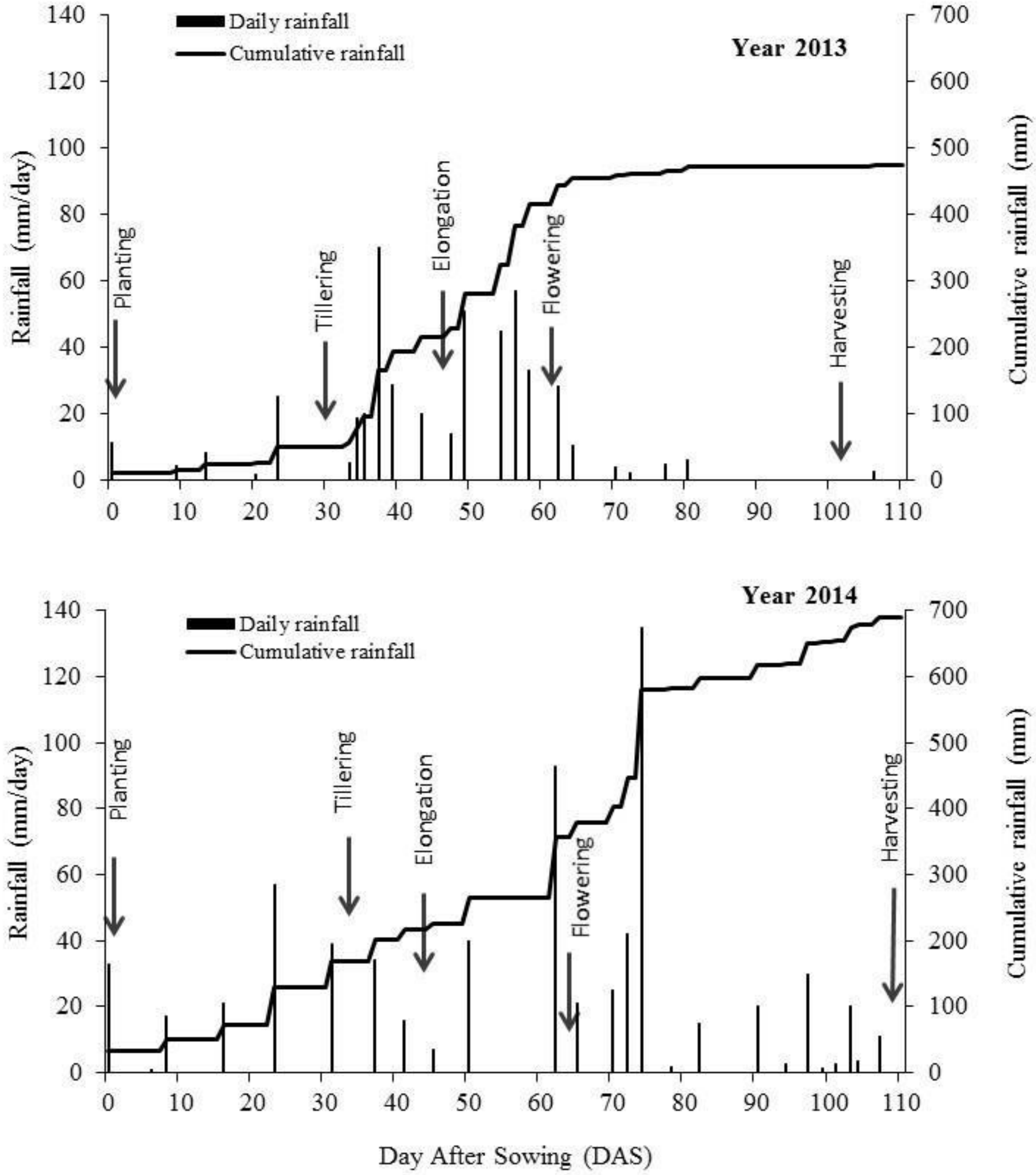

Figure: 5.1. Rainfall distribution during the cropping period

5.3.2. Effect of treatments on grain and total dry matter yields

Grain yield and total dry matter yield as affected by the treatments are shown in Table 5.2 and the summary of analysis of variance is presented in Table 5.3. The grain yields were significantly (P < 0.001) affected by the planting seasons; the highest grain yields were recorded in 2014 compared to 2013. There was, a significant difference (P < 0.001) in grain yield between fertilizer micro-dosing options; the grain yield recorded with 2 g DAP hill^{-1} was significantly higher than that of 6 g NPK hill^{-1} treatments. Similarly, the total dry matter (TDM) production was highest with 2 g DAP hill^{-1} compared with the 6 g NPK hill^{-1} treatments. The grain yields were much lower in the fertilizer micro-dosing treatment plots compared with those receiving the combined application of fertilizer micro-dosing and manure. There was, a marked increase in millet grain yield when manure was added to fertilizer micro-dosing treatments (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) regardless of the mode of manure application. Adding manure to fertilizer micro-dosing increased millet grain yields on average by 59%, 83% and 113%, respectively for the 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1} application rates. The hill placement of manure performed better in improving millet grain yield irrespective of the fertilizer micro-dosing options. However, there was, no significant interaction between fertilizer micro-dosing options and the mode of manure placement in grain millet yield.

Table: 5.2. Effect of the treatments on the grain yield and total dry matter

		Grain yield (kg ha^{-1})		Total dry matter (kg ha^{-1})	
Fertilizer micro-dosing option	Manure rate (kg ha^{-1})	2013	2014	2013	2014
2 g DAP hill^{-1}	0	354±57	876±24	1642±135	3963±171
	1000	503±78	1336±56	2031±149	5118±290
	2000	762±34	1429±78	2534±316	5619±335
	3000	758±97	1751±73	2529±229	6809±302
6 g NPK hill^{-1}	0	237±13	753±33	1068±126	3729±110
	1000	456±58	1230±80	1953±481	4438±294
	2000	511±54	1354±98	1973±382	5091±335
	3000	784±92	1443±55	2926±493	5020±346
Manure placement mode					

Broadcasting	527±41	1202±108	1864±60	4472±149
Hill placement	564±56	1341±193	2300±73	5475±279

± Standard error of mean

The TDM significantly increased with increasing level of manure regardless of the fertilizer micro-dosing treatments. The highest TDM was recorded with hill placement of manure compared with broadcasting of the same rate of manure. Hill placement of manure significantly increased TDM production on average by 23% in 2013 and 22% in 2014 as compared to manure broadcasting.

Table: 5.3. Summary of analysis of variance on grain yields and total dry matter

		F pr.	
Source of variation	d.f.	Grain yield	Total Dry Matter
Block stratum	2		
Fertilizer micro-dosing option	1	<.001	<.001
Manure rate	3	<.001	<.001
Manure placement mode	1	0.002	<.001
Year	1	<.001	<.001
Fertilizer micro-dosing option x manure rate	3	0.709	0.759
Fertilizer micro-dosing option x manure placement mode	1	0.796	0.066
Manure rate x manure placement	3	0.285	0.006
Fertilizer micro-dosing option x year	1	0.313	0.009
Manure rate x year	3	<.001	0.156
Manure placement x year	1	0.064	0.021
Fertilizer micro-dosing option x manure rate x manure placement	3	0.753	0.417
Fertilizer micro-dosing option x manure rate x year	3	0.015	0.001
Fertilizer micro-dosing option x manure placement x Year	1	0.98	0.421
Manure rate x Manure placement x Year	3	0.316	0.574
Fertilizer micro-dosing option x manure rate x manure placement x Year	3	0.421	0.474
Residual	62		
CV (%)		24.6	26.0

5.3.3. Effect of treatments on water use efficiency

Water use efficiencies in grain yield and in total dry matter production are presented in Table 5.4 and the summary of the analysis of variance is shown in Table 5.5. Water use efficiency (WUE) in grain yield was relatively very low with fertilizer microdosing treatments alone. There was, an additive effect of manure and fertilizer microdosing on grain yield water use efficiency. WUE in grain yield was markedly increased on average by 68%, 129% and 144%, respectively when 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg of manure ha^{-1} were added to fertilizer micro-dosing. The method of manure placement improved the grain water use efficiency; WUE in grain yield was increased on average by 18% with manure hill placement compared with broadcasting of manure. Similarly, the total dry matter WUE was significantly ($P < 0.001$) improved with manure application. WUE in total dry matter was significantly ($P < 0.001$) increased (on average by 35%) with manure hill placement as compared to broadcasting.

Table: 5.4. Grain and total dry matter (TDM) water use efficiencies (WUE)

Fertilizer micro-dosing option	Manure rate (kg ha^{-1})	WUE Grain (kg mm^{-1}) 2013	WUE Grain (kg mm^{-1}) 2014	WUE TDM (kg mm^{-1}) 2013	WUE TDM (kg mm^{-1}) 2014
2 g DAP hill^{-1}	0	0.9 ± 0.1	2.0 ± 0.1	4.9 ± 0.3	7.8 ± 0.3
	1000	1.7 ± 0.4	2.8 ± 0.3	6.5 ± 1.0	11.6 ± 1.9
	2000	2.8 ± 0.7	3.3 ± 0.7	9.0 ± 1.3	13.5 ± 3.4
	3000	2.3 ± 0.4	3.5 ± 0.3	8.3 ± 1.0	13.8 ± 2.5
6 g NPK hill^{-1}	0	0.7 ± 0.1	1.7 ± 0.2	4.1 ± 0.9	8.7 ± 0.6
	1000	1.3 ± 0.4	2.7 ± 0.3	5.7 ± 1.3	10.5 ± 1.7
	2000	2.0 ± 0.6	2.9 ± 0.2	7.9 ± 2.2	11.4 ± 0.4
	3000	2.8 ± 0.4	3.0 ± 0.2	11 ± 1.4	11.1 ± 0.9
Manure placement					
Broadcasting		1.8 ± 0.1	2.4 ± 0.4	6.4 ± 0.4	9.1 ± 0.5
Hill placement		1.9 ± 0.3	3.1 ± 0.2	8.0 ± 1.1	13.0 ± 1

± Standard error

5.3.4. Effect of treatments on root length density

The effect of manure placement on vertical root length density (RLD) is illustrated in Figure 5.2. The millet RLD was mostly concentrated in soil layer of 0-20 cm from tillering to dough stage and dropped drastically in deeper soil layers. The RLD tended to be higher in the topsoil with manure hill placement compared with broadcast; but in the deeper soil layer roots became significantly (P < 0.001) denser with broadcasting of manure (Table 5.6). This increase of RLD in subsoil with broadcasting of manure was particularly important at dough stage in 2013 when the crop experienced rainwater shortage. The root distribution in the lateral direction was however, markedly higher with manure hill placement in all the soil depths compared with manure broadcast (Figure 5.3). At the early millet growth stage (tillering), the total lateral RLD was increased by 66% and 42% in manure hill placement, respectively at 25 cm and 50 cm from the hill centre compared with manure broadcast. Similarly, at the dough stage, manure hill placement exhibited greater root distribution pattern in topsoil and deeper soil layers compared with manure broadcast.

Table: 5.5. Summary of analysis of variance on water use efficiencies (WUE)

		F pr.	
Source of variation	d.f.	WUE in Grain	WUE in TDM
Block stratum	2		
Fertilizer micro-dosing option	1	0.194	0.376
Manure rate	3	<.001	<.001
Manure placement mode	1	0.072	<.001
Year	1	<.001	<.001
Fertilizer micro-dosing option x manure rate	3	0.754	0.754
Fertilizer micro-dosing option x manure placement mode	1	0.48	0.106
Manure rate x manure placement	3	0.753	0.117
Fertilizer micro-dosing option x year	1	0.77	0.327
Manure rate x year	3	0.765	0.66
Manure placement x year	1	0.203	0.1
Fertilizer micro-dosing option x manure rate x manure placement	3	0.901	0.78
Fertilizer micro-dosing option x manure rate x year	3	0.677	0.254
Fertilizer micro-dosing option x manure placement x year	1	0.475	0.197
Manure rate x manure placement x year	3	0.829	0.696

Fertilizer micro-dosing option x manure rate x manure placement x year	3	0.615	0.218
Residual	62		
CV (%)		27	28.3

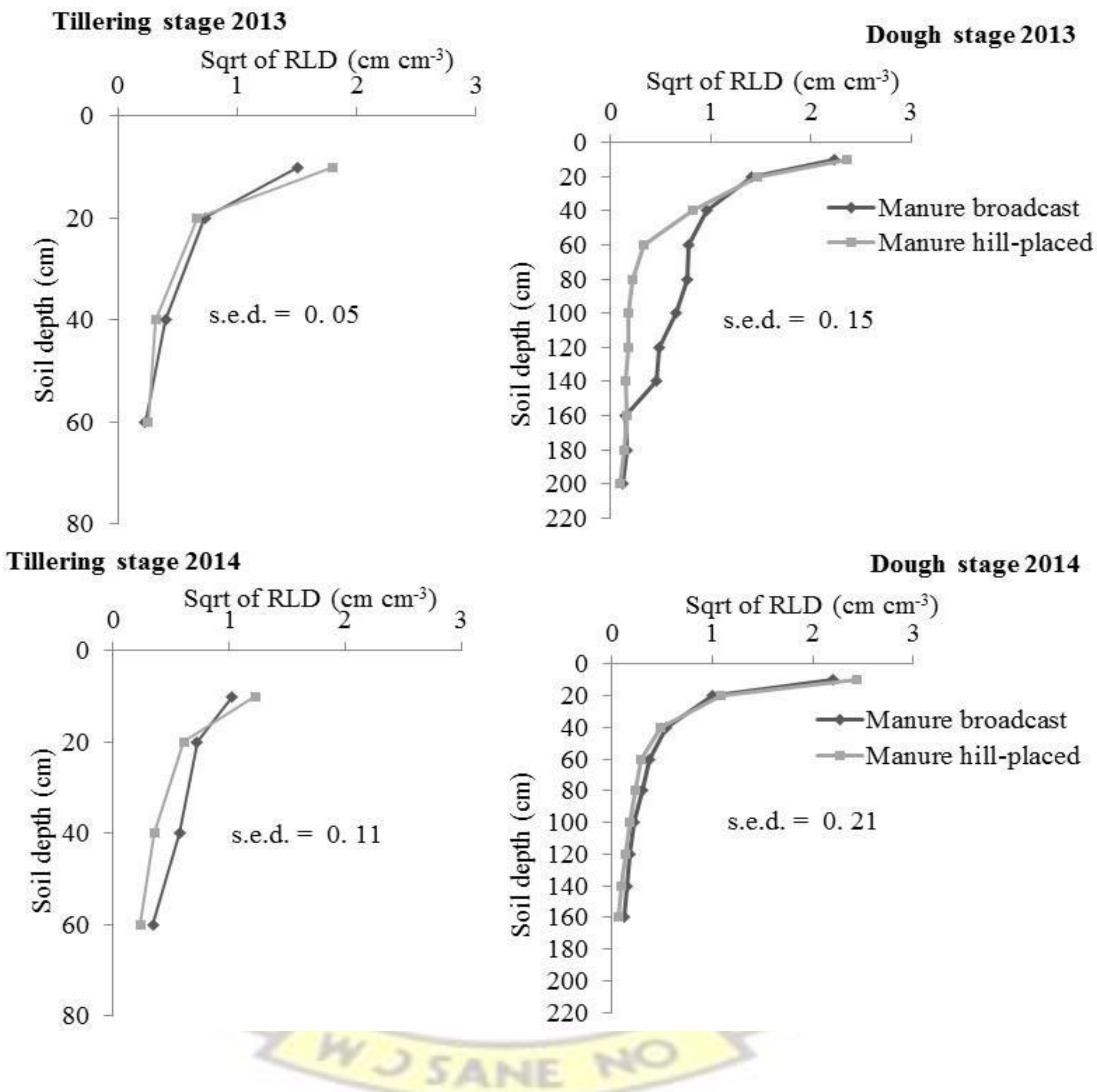

Figure: 5.2. Effect manure placement on vertical root length density of millet

Table: 5.6. Probability values of root length density with respect to different treatments

	Tillering stage	Dough stage

	0-20 cm	40-100 cm	0-20 cm	40-100 cm	120-200 cm
Fertilizer micro-dosing option (F)	NS	NS	NS	NS	NS
Manure rat (M)	0.042	<.001	<.001	0.009	NS
Manure placement (P)	NS	0.025	0.02	0.036	NS
F x M	NS	<.001	NS	0.007	NS
F x P	NS	ns	NS	NS	NS
M x P	NS	0.019	NS	0.018	NS
F x M x P	NS	0.01	NS	NS	NS

NS = Not significant

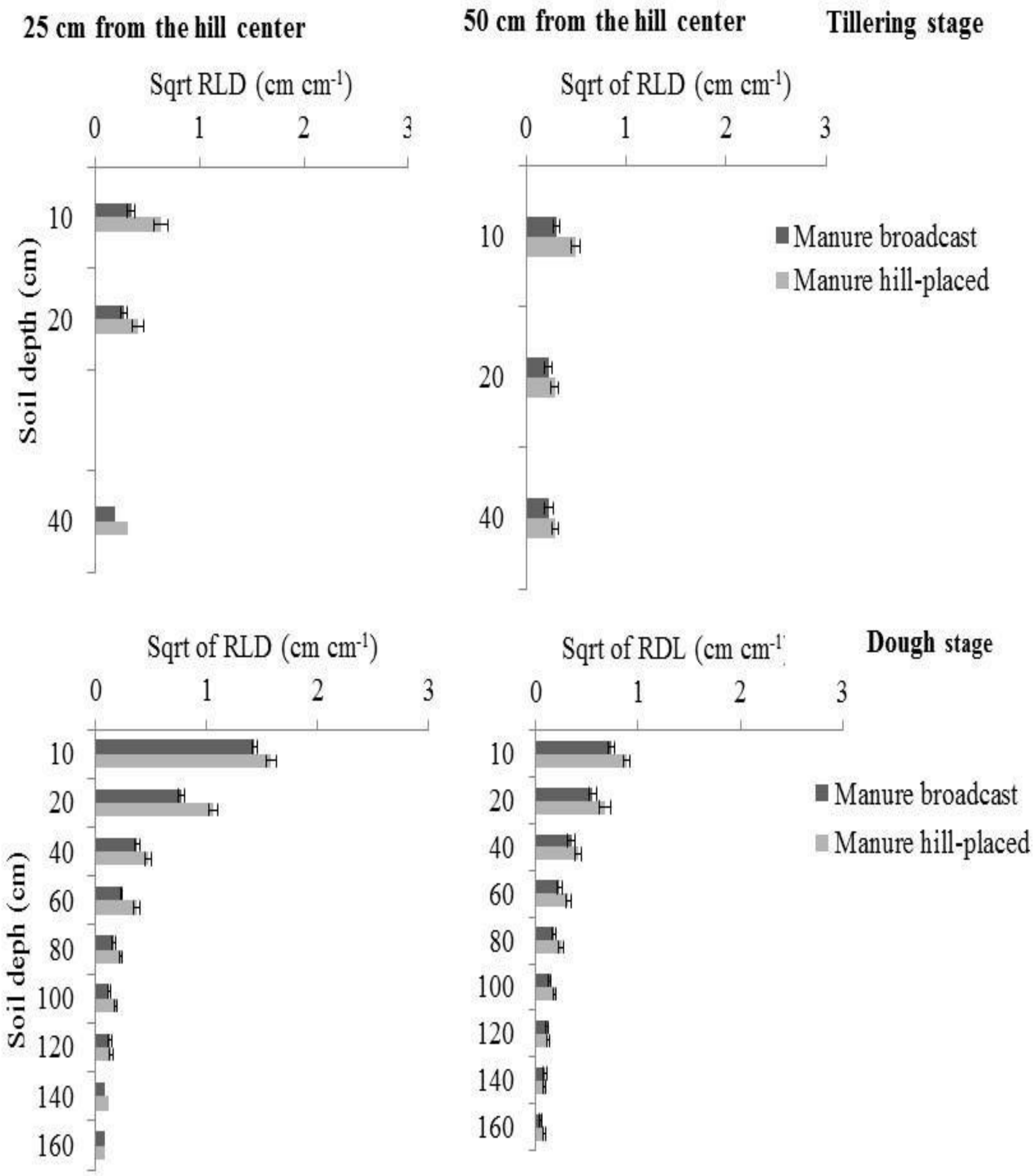

Figure: 5.3. Effect of manure placement method on lateral root length density

5.4. Discussion

Lack of reliable rainfall often obscures the positive response of a crop to a soil fertility management strategy aimed at increasing crop productivity in the Sahelian agroecological zone of Niger (Bationo *et al.*, 1990; Eyshi Rezaei *et al.*, 2014). The mean grain yield response to fertilizer and manure applications recorded in 2013 were relatively low and were attributed to the low and irregular distribution of rainwater during the reproductive stage (Figure 5.1). Although it is adapted to dry conditions, pearl millet is sensitive to water shortage especially when this occurs during the flowering stage as was the case in the current study in 2013. The low millet grain yield observed in 2013 is rather similar to those reported earlier for the Sahel (Bieler *et al.*, 1993; Rockström and de Rouw, 1997; Winkel *et al.*, 1997; Sivakumar and Salaam, 1999; Graef and Haigis, 2001). Yet, millet responded positively to the nutrient management treatments imposed. Manure application improved millet yield and total dry matter production significantly as compared to the no-manure treatments (Table 5.2). There was, a significant increase in millet yield and total dry matter production when manure was added to the fertilizer micro-dosing (Table 5.3).

The positive effect of manure on millet yields can be attributed not only to the supply of additional nutrients such as Ca and Mg (Bayu *et al.*, 2005; Zingore *et al.*, 2008) which are lacking in sufficient quantities in this experimental sandy soil (Table 5.1). But this positive effect can also be explained by the low level of organic matter content which limits soil water and nutrient retention in this extremely sandy soil. Liu *et al.* (2013) demonstrated that applications of fertilizer and manure not only accelerated the improvement of soil fertility but also maintained soil water balance, and significantly improved crop yields in the short term. The current results show once more the need for improving soil organic matter in order to enhance millet productivity in low input rainfed farming systems.

The results of the present study confirmed earlier reports that showed the positive response of crop to N fertilizer in soil rich in organic matter while the application of the same level of fertilizer in the soil poor in organic matter led to no significant crop response (Zingore *et al.*, 2008). The method of manure application improved millet yields markedly. The hill placement of manure performed better in improving millet grain yield and dry matter than broadcasting, irrespective of the fertilizer micro-dosing option (Table 5.3). It, is possible that the positive effect of hill placement of manure could have resulted from a better scavenging of the limited amount of nutrients by the roots due to early root proliferation favoured by hill placement of manure (Figure 5.2 and 5.3). The concentration of manure in the vicinity of crop rooting system such was the case in hill application of manure, led to the creation of a "micro-climate" around the plant root system which results in the rapid early root growth leading to better use of nutrients and rainwater. Smit *et al.* (2013) argue that enhancing early root growth could stimulate uptake of soil nutrients such as phosphorus because of high capacity of young roots in improving nutrients uptake capacity.

Increased in grain and biomass yields due to the combining application of fertilizer micro-dosing and manure was accompanied by an increase in the water use efficiency (Table 5.4). Viets (1962) explained that since the evapotranspiration is little affected by the management, as was the case in the current study, any factor that increases yield will increase WUE. These results, are consistent with the earlier studies which reported an increment of millet water use efficiency in response to soil fertility management options in the Sahelian zone due to increase in biomass production (Payne, 1997;

Yamoah *et al.*, 2002; Manyame, 2006; Akponikpé *et al.*, 2008). The results of the present study are also in agreement with the findings of Wang *et al.* (2013) for maize. The results, obtained in the current study, indicate that the water use efficiency can be improved through an efficient use of the limited organic resources available for the smallholder farmers in the Sahel.

There was marked increase in vertical root length density (RLD) values from tillering to dough stage in the topsoil (0-20 cm) ranging from 2.7 to 5.7 cm cm^{-3} and 3.4 to 6.5 cm cm^{-3}, respectively for manure broadcast and hill placement (Figure 5.2). These values were in close agreement with those reported by Hafner *et al.* (1993) and Ibrahim *et al.* (2014). The vertical RLD tended to be higher in the topsoil (0-20 cm) with manure hill placement. The root length increase influenced by the hill placement of manure can be attributed to roots behaviour tending to be more profuse in root zones where nutrients are mostly concentrated (Hodge, 2004). The greater RLD obtained with manure hill placement in the topsoil indicates a strategy adopted by millet and many other crops to invest in roots where the return is highest (Hodge, 2009). Roots tended to penetrate into deeper soil layers probably to scavenge for water in the case of manure broadcasting in 2013 when the crop experienced a long dry spell during the reproductive phase (Figure 5.1). Higher root growth was observed by Hafner *et al.* (1993) when the rainfall was unfavourable; and by Yamauchi *et al.* (1996) who showed that there was concentration of roots in the deeper soil layers under drought condition. A high root length density in deeper soil profile was important for the crop because it could make use of water in the subsoil to cope with the dry spells and also utilize nutrients leached in the deeper soil layer (Wiesler and Horst, 1997; Brück *et al.*, 2003).

5.5. Conclusion

The results of the current study showed that millet production could be improved further by combining the fertilizer micro-dosing technology with the placement of manure. Based on the results of this study, the hill-placement of 2000 kg ha^{-1} of manure and 20 kg ha^{-1} of DAP appeared to be the most effective combination for improving millet yield, and water use efficiencies in the Sahelian millet-based systems. However, hill application of manure requires further labour investment for digging the holes which can be a constraint on the adoption of this technology. Consideration of the economic benefits will surely guide farmers' decision to the adoption of this technology. There is, therefore a need to test the economic viability of this technology to enhance its adoption by the farmers.

Chapter Six

Assessing nutrient balances in millet cropping system under fertilizer micro-dosing

Fertilizer micro-dosing increases the risk of soil nutrients depletion in input pearl millet-based cropping system. Submitted to *Agronomy for Sustainable Development*

Chapter Six

6. Assessing nutrient balances in millet cropping system under fertilizer micro-dosing

Abstract

Over the years, scarcity of information on the nutrient gains or losses has led to overemphasis being placed on crop yields and economic income as the direct benefits from the fertilizer micro-dosing technology. There is, increasing concern about the sustainability of this technology in small-scale Sahelian cropping systems. This study was designed to establish nutrient balances under fertilizer micro-dosing technology. Fertilizer micro-dosing treatments alone (2 g DAP hill^{-1}, 6 g NPK hill^{-1}) and along with manure application (1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1} rates) were arranged in RCBD with three replications. The partial nutrients balances were -37 kg N ha^{-1}yr^{-1}, -1 kg P ha^{-1}yr^{-1}, -34 kg K ha^{-1}yr^{-1} in plots that received the application of 2 g DAP hill^{-1} and -31 kg N ha^{-1}yr^{-1}, -1 kg P ha^{-1}yr^{-1}, -27 kg K ha^{-1}yr^{-1} for 6 g NPK hill^{1}. The transfer of straw yields accounted for 66% N, 55% P and 89% K for removal. The annual full nutrient balances with fertilizer micro-dosing treatments were on average - 44 kg N ha^{-1}yr^{-1}, -7 kg P ha^{-1}yr^{-1} and -22 kg K ha^{-1}yr^{-1} which represent 7%, 24% and 10% of N, P and K stocks, respectively. Fertilizer micro-dosing increases the risk of soil nutrients depletion. Hence, to reverse the soil nutrients mining effect of fertilizer micro-dosing technology in low-input millet cropping system, crop residues recycling must be considered.

Keywords: Fertilizer micro-dosing, sustainability, nutrient balances, nutrients stocks, millet

6.1. Introduction

Soil nutrient depletion is a major constraint to ecological agricultural production in Sub-Saharan Africa (Drechsel *et al.*, 2001; Cobo *et al.*, 2010). Earlier report on soil nutrient balances from several African countries indicate that soil nutrients are depleted at alarming rates (Smaling *et al.*, 1993; Henao *et al.*, 2001). In the Sahelian countries where the low-input small-scale farming systems are predominant, such depletion of soil fertility is not unusual.

In Niger, most of the soils allocated for crop production are degraded and characterized by low availability of soil nutrients including nitrogen and phosphorus (Manu *et al.*, 1991; Gandah *et al.*, 2003b). Increasing crop production under such conditions should necessary benefit from improved soil nutrients availability. Application of inorganic fertilizers plays a crucial role in increasing yields and reducing soil nutrients 'mining' (Bindraban *et al.*, 2014). However, the use of mineral fertilizer remains very low in Niger and represents only less than 5 kg ha^{-1} yr^{-1} according to the Fertilizer Summit held in Abuja, Nigeria in 2006. The high cost of inorganic fertilizer relative to the income of small-scale farmers and the risk associated with its application in dry spell-prone areas, are the major constraining factors for fertilizer use in Niger (Abdoulaye and Sanders, 2005).

Several soil fertility management options to enhance pearl millet productivity on Sahelian sandy soils in Niger has been developed (Bationo *et al.*, 1998b). Fertilizer micro-dosing technology which consists of the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing (ICRISAT, 2009) is becoming the most common technology employed by small-scale farmers across Sub-Saharan West Africa (Bationo and Waswa, 2011; Buerkert and

Schlecht, 2013). This technology has been promoted to improve crop yield, fertilizer use efficiency and income in small-scale cereal-based systems (Tabo *et al.*, 2007).

Over the years, scarcity of information on complete evaluation of nutrient gains or losses has led to overemphasis on crop yields and economic income generated through fertilizer micro-dosing technology (Aune and Ousman, 2011; Bagayoko *et al.*, 2011; Tabo *et al.*, 2011; Bielders and Gérard, 2014). However, evaluation of its sustainability has received less attention and the research community continues to believe that the small dose of mineral fertilizer applied results in higher crop yields and thus high nutrient uptake (Hayashi *et al.*, 2008; Ibrahim *et al.*, 2014). The debate concerning the increase of soil nutrient depletion risk under fertilizer micro-dosing technology is intensifying (Breman, 2012; Buerkert and Schlecht, 2013; Aune and Coulibaly, 2015).

Recently, Camara *et al.* (2013) reported that "micro-dosing complied with all except agronomic sustainability, because in the long term it may cause nutrient depletion of the soil and consequently, decreased soil fertility and crop productivity". Camara and co-workers supported their statement from nutrient uptake data recorded under fertilizer micro-dosing which corresponded to 34-75 kg N ha^{-1} and 8-20 kg P ha^{-1} compared with 6.1 kg N ha^{-1} and 15.6 kg P ha^{-1} applied. It is clear that the increase in yield results in greater extraction of soil nutrients which could lead to the depletion of soil nutrient stocks and eventually to the decline in crop yields (Vanlauwe and Giller, 2006). However, it seems simplistic to assess the long-term sustainability of a technology or a system on the basis of partial nutrient balance exclusively as was argued by the authors cited above. Nutrient balances (whether partial or full) cannot be used as sustainability indicator without consideration of nutrient stocks in the soil (Vanlauwe and Giller, 2006). According to Hilhorst *et al.* (2000), agricultural practice with a stock decline for total nitrogen of more than 1 % was considered not sustainable.

The objective of the current study was, therefore, to establish the nutrient balances under fertilizer micro-dosing technology and their implications on soil nutrient stock.

6.2. Materials and methods

6.2.1. Experimental site description

The experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Station, Sadoré, Niger (13˚ 15’ N and 2˚ 18’ E, 240 m asl). The climatic conditions are typical of the southern edge of the Sahelian zone, with rainfall and high temperature throughout the year (Sivakumar *et al.*, 1993). The mean annual rainfall (1983-2014) at the Research Station of Sadoré is 551 ± 110 mm and the average temperature is 29°C (ICRISAT, climate database). The soil was classified as a Psammentic Paleustalf and isohyperthermic in the USDA Soil Taxonomy and as a Luvic Arenosol by the FAO system (West *et al.*, 1984). The soil of the experimental field is very strongly acid (pH 4.7 - 5.1) with low level of organic carbon (0.31%) in the topsoil depth (0-10 cm) (Table 6.1). The total N content ranged from 311 mg kg^{-1} at 0-10 cm down to 135 mg kg^{-1} within 20 to 40 cm soil depth. The extractable P content was 8.9 mg kg^{-1} in the topsoil (0-10cm) and 3.7 mg kg^{-1} within 20 to 40 cm soil depth. The properties of this soil are representative of the soils in Niger characterized by sandy texture and low levels of nutrients and organic matter (Manu *et al.*, 1991).

6.2.2. Experiment set-up

The experiment was carried out in 2013 and 2014 rainy seasons. Two fertilizer microdosing options alone (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) and along with three application rates of manure (1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}) and relevant control treatment were arranged in randomized complete block design (RCBD) with three replications. Manure was applied before sowing in the planting hole at the rates of 100 g hill^{-1}, 200 g hill^{-1} and 300 g hill^{-1} corresponding to 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}, respectively. The fertilizer micro-dosing rates were applied at planting at 2 g DAP hill^{-1} and 6 g NPK hill^{-1} corresponding to 20 kg ha^{-1} of DAP (diammonium phosphate) and 60 kg ha^{-1} of compound fertilizer NPK (15-15-15), respectively. The quantity of nutrient content in each treatment is given in Table 6.4. Around 15 seeds of improved pearl millet variety ICMV-IS 89305 (110 maturity days) were sown in the planting hill at the spacing of 1 x 1 m (10,000 hills ha^{-1}). Each individual treatment plot (5 m x 6 m) was separated by a 1 m alley. Three weeks after planting, the millet hills were thinned to three plants per hill. There were three weeding events during the growing period. To determine straw and grain yields, the straw samples and millet panicles threshed by hands were collected from the harvested area of 4 m x 5 m (20 m^2), sun-dried, weighed and expressed in kg ha^{-1}.

Table: 6. 1. Initial soil characteristics of experimental field

Parameters	0-10 cm	10-20 cm	20-40 cm
Soil texture			
Sand (%)	94.1	95.0	92.1
Silt (%)	3.8	2.2	2.1
Clay (%)	2.0	2.8	5.4
Bulk density (g cm^{-3})	1.6	1.6	1.5
Soil chemical properties pH-			
H_2O (1:2.5)	5.1	4.9	4.7
pH-KCl (1:2.5)	4.8	4.1	3.9
Organic C (%)	0.3	0.2	0.1
Total N (mg kg^{-1})	311	170	135
Available P (mg kg^{-1})	8.9	7.7	7.2
Ca^{2+} (cmol$_c$ kg^{-1})	1.0	1.3	0.8
Mg^{2+} (cmol$_c$ kg^{-1})	0.4	0.6	0.3
Na^+ (cmol$_c$ kg^{-1})	0.01	0.01	0.01
K^+ (cmol$_c$ kg^{-1})	0.17	0.16	0.17
H^+ (cmol$_c$ kg^{-1})	0.1	0.1	0.2
Al^{3+} (cmol$_c$ kg^{-1})	0.0	0.2	0.3

6.2.3. Soil and plant sampling and analysis

At the onset of the experiment, soil samples were collected from the experimental field at 0-10 cm, 10-20 cm and 20-40 cm in each treatment plot for initial chemical and physical characterization. The samples were taken to the laboratory for determination of pH (1: 2.5 soil/water ratio), exchangeable acidity (H^+ and Al^{3+}) was extracted by 1 M KCl solution and titrated with 0.025 M NaOH (van Reeuwijk, 1993). The exchangeable bases were determined by extraction with 0.01 M AgTU (Silver thiourea complex cation) and the cation concentrations measured on atomic absorption spectrophotometer (van Reeuwijk, 1993), Organic carbon was determined using Walkley and Black's method as described by van Reeuwijk (1993). The total N was determined by Kjeldahl method (Houba *et al.*, 1995) and available phosphorus by the Bray 1 method (van Reeuwijk, 1993). Bulk density (*BD)* was determined by the core method (Blake and Hartge, 1986). The particle size distribution was determined using Robinson method as described by ICRISAT Soil and plant laboratory. At harvest, entire plants were sampled from two representative pockets (hills) in each treatment plot. The samples were separated into leaves, stems, glumes and grains which were sun-dried thereafter. The dried samples were milled and sub-samples were subjected to total nitrogen (N), phosphorus (P) and potassium (K) analysis. Total nitrogen was analyzed by Kjeldahl methods using a mixture of salicylic acid, H_2SO_4 and selenium for the digestion. The quantitative determination of total N was done with an autoanalyser using the colorimetric method based on the Bertholet reaction (Houba *et al*. 1995). The same digest was used to determined total P and K. Total P was quantified with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid and total K was determined with flame emission spectrophotometry (Houba *et al.*, 1995). The laboratory protocols for soil and plant chemical and physical properties analyses were provided in details in Chapter 3.

6.2.4. Calculations

6.2.4.1. Nutrient stocks

The stocks of N, P and K in each treatment plot were calculated from the formula used by Bond (2010) as follows:

$$Stock\ (kg\,ha^{-1}) = Nutrient\ concentration\ (mg\,kg^{-1}) \times bulk\ density\ (kg\,m^{-3}) \times soil\ depth\ (m) \times 10^{-2} \quad [6.1]$$

6.2.4.2. Nutrient balances

The partial nutrient balances at plot level were calculated by subtracting the quantity of nutrients removed in the harvested products, grain (OUT1) and crop residue (OUT2) from the corresponding total quantities of nutrients applied through mineral fertilizer (IN1) and manure (IN2) in each treatment plot. The OUT1 and OUT2 were calculated as follows:

$$OUT1 = Grain\ yield\ (kg\,ha^{-1}) \times nutrient\ content\ of\ grains\ (kg\,kg^{-1}) \quad [6.2]$$

$$OUT2 = Crop\ residue\ removed\ (kg\,ha^{-1}) \times nutrient\ content\ of\ crop\ residue\ (kg\,kg^{-1}) \quad [6.3]$$

The full nutrient balance at plot level was calculated by estimating the difference in the different nutrient flows. Following the approach of Stoorvogel and Smaling (1990), four major inputs (IN1-4) and five major outputs of nutrients (OUT1-5) were identified in the current study (Table 6.2). The difficult-to-quantify flows (not measured) were calculated from the transfer functions and the secondary data from the literature as described below. It is worthy to note that input IN5 (sedimentation) which referred to the nutrient inputs in irrigation water and input in sediment as a result of water erosion was not taking into account in this study due to the fact that the experiment was conducted without irrigation system and also the naturally flooded water was neglected as a result of the sandy texture of the experimental field.

Table: 6.2. Codification of calculated or estimated nutrient flows

Code	Flows
Inputs	
IN 1:	Inorganic fertilizer
IN 2:	Organic amendment
IN 3:	Wet and dry depositions
IN 4:	Biological nitrogen fixation
Outputs	
OUT 1:	Harvested product (grain yield)
OUT 2:	Crop residue
OUT 3:	Leaching
OUT 4:	Gaseous losses
OUT 5:	Erosion

6.2.4.2.1. Estimation of inputs not directly measured in this study

- Atmospheric depositions (IN3)

The input of nutrients by atmospheric depositions consists of two components: wet deposition associated with rainfall and dry deposition related to Harmattan dust. The N and P depositions from the rainfall were calculated using the formulae developed by de Ridder *et al.* (1982) as follows:

$$Ndep = 0.0065 \times Annual\ precipitation\ (mm) \quad [6.4]$$

$$Pdep = 0.0007 \times Annual\ precipitation\ (mm) \qquad [6.5]$$

where, Ndep is Nitrogen from rainfall depositions and Pdep phosphorus from rainfall depositions.

The correlations between atmospheric deposition and rainfall found by de Ridder *et al.* (1982) (equations [6.4] and [6.5]) were suitable for the Sahelian zone with an average annual rainfall generally less than 700 mm. These equations were found appropriate for the study area where the total rainfall recorded were 475 mm and 689 mm in 2013 and 2014, respectively. Therefore, the Ndep values of 3.09 and 4.49 were assumed to apply for 2013 and 2014, respectively. These values are close to 3.5 kg N ha^{-1} yr^{-1} reported in South-West of Niger (570 mm rainfall) by Buerkert and Hiernaux (1998). Phosphorus values from rainfall depositions (Pdep) derived from the equation [6.5] were set to be 0.33 kg ha^{-1} yr^{-1} in 2013 and 0.48 kg ha^{-1} yr^{-1} in 2014.

The Potassium from rainfall deposition was calculated with the transfer function developed by Roy and Misra (2003) as follows:

$$K_2Odep = 0.11 \times \sqrt{Annual\ precipitation\ mm}\ (\ ) \qquad [6.6]$$

where K2O dep is potassium deposition from rainfall.

The values of K2O obtained from the equation [6.6] were multiplied by 0.83 to convert K2O to K. Estimated values for potassium deposition from rainfall were 2.0 kg ha^{-1} yr^{-1} and 2.4 kg ha^{-1} yr^{-1}, respectively in 2013 and 2014.

In addition to the quantity of N, P and K calculated from rainfall deposition, 3 kg N ha^{-1} yr^{-1}, 1 kg P ha^{-1} yr^{-1} and 15 kg K ha^{-1} yr^{-1} were added as the amount of nutrients deposited annually with the dust load in Niger (Buerkert and Hiernaux, 1998). The total nutrients from atmospheric depositions estimated as nutrients inputs via rainfall and harmattan dust in the current study were therefore set to be 6.09 kg N ha^{-1} yr^{-1}, 1.33 kg P ha^{-1} yr^{-1}and 17 kg K ha^{-1} yr^{-1} in 2013; 7.49 kg N ha^{-1} yr^{-1}, 1.48 kg N ha^{-1} yr^{1} and 17.4 kg N ha^{-1} yr^{-1} in 2014.

- Biological nitrogen fixation (IN4)

Nitrogen fixed from the atmosphere is generally an important source of nitrogen input in several agricultural cropping systems. Input by biological nitrogen fixation (BNF) consists of diverse parts, i.e. symbiotic N fixation by leguminous crops and nonsymbiotic N fixation. It is worthy to note that the symbiotic nitrogen fixation was not considered in the current study because the study dealt with a cereal in mono-cropping system. The non-symbiotic N fixation (expressed in kg N ha^{-1}) was estimated using the equation developed by Roy and Misra (2003) as follows:

$$N\ fixed = 0.5 + 0.1\sqrt{precipitation\ mm} \qquad [6.7]$$

The values of non-symbiotic N fixation were therefore 2.7 kg N ha^{-1} and 3.1 kg N ha^{-1}, respectively in 2013 and 2014. These non-symbiotic N values fall in the range of nitrogen fixation values (1 to 5 kg N ha^{-1} yr^{-1}) reported the in Sahelian rangelands by Kurl *et al.* (1982).

6.2.4.2.2. Estimation of outflows not directly measured in this study

- Leaching (OUT3)

The leaching losses were considered for N and K. Phosphorus is often strongly bound by soil particles. The extent of the losses depends on soil physical properties (texture and structure), quantities of N and K applied, and soil nutrient retention capacity, crop species, amount and distribution of rainwater.

The quantities of N lost annually through leaching were estimated from the transfer function established by de Willigen (2000) as follows:

$$OUT3\ N = 21.37 + \frac{P}{C \times L}(0.0037 \times Nf + 0.0000601 \times OC - 0.00362 \times Nu) \qquad [6.8]$$

Where P is annual precipitation (mm yr^{-1}), *C* is the clay content (%) of the topsoil, L is rooting depth (m), Nf is N applied through mineral fertilizer and/or organic fertiliser (kg ha^{-1}), OC is organic carbon content (%) of the topsoil and Nu = N uptake by the crop (kg ha^{-1} yr^{-1}).

The amount of K lost through leaching was calculated using the formula described by Smaling *et al.* (1993) as follows:

$$OUT3\ K = (Ke + Kf) \times (0.00029 \times precipitation + 0.41) \qquad [6.9]$$

Where Ke is the exchangeable K ($cmol_c$ kg^{-1}) in the top soil and Kf is the amount of K derived from applied amendment.

- Gaseous losses (OUT 4)

Gaseous N losses from the soil was estimated from a regression model developed by Roy and Misra (2003). The equation consisted of two parts: regression model for the N_2O losses through denitrification and a direct loss factor for volatilization of NH_3 as follows:

$$OUT4 = (0.025 + 0.000855 \times P + 0.01725 \times F + 0.117 \times OC) + 0.113 \times F \qquad [6.10]$$

Where P is the rainfall (mm); F is the amount of nitrogen in mineral and organic fertilizers (kg N ha^{-1}); OC is the organic carbon content (%).

- Erosion (OUT5)

According to Buerkert and Hiernaux (1998), wind erosion is often described as the major threat to soil productivity and crop yield on the unprotected sandy soils of Niger characterized by 95% sand content. The data (11 kg N ha^{-1} yr^{-1} , 7.1 kg P ha^{-1} yr^{-1} and 5.4 kg K ha^{-1} yr^{-1}) published by Buerkert *et al.* (1996), on soil nutrients losses due to wind erosion at the plot level in millet field were considered as OUT5 in the current study.

The full nutrient balances were therefore quantified as follows:

$$Nutrientbalance = (IN1 + IN2 + IN3 + IN4) - (OUT1 + OUT2 + OUT3 + OUT4 + OUT5) \quad [6.11]$$

The details of codes used are given in Table 6.2.

6.2.4.3. Stock to nutrient balance ratio

The nutrient stock to nutrient balance ratio which gives an indication of time a cropping system could sustain production at the same level with the available nutrients was calculated using the formula given by Defoer *et al.* (2000) as follows .

$$\mathrm{NSB} = \frac{Nutrientstock}{Fullnutrientbalance} \quad [6.12]$$

6.2.5. Data analysis

Prior to the analysis, data were carefully checked for normal distribution in GENSTAT v.9 using Distributions options. Thereafter, the analysis of variance was, therefore, performed with GENSTAT v.9 9 using a One-way ANOVA option (Trust, 2007). Each fertilizer micro-dosing option x manure combination was considered as a single treatment. Differences among treatments were considered at error probabilities ≤ 0.05.

6.3. Results

6.3.1. Soil nutrient stocks

Total stocks of N, P and K in the upper 20 cm of the soil depth ranged from 562 to 695 kg N ha^{-1}, with 12 - 48 kg ha^{-1} as available P and 166 - 289 kg ha^{-1} as exchangeable K (Table 6.3). The level of N stock is low. However, the extractable P and exchangeable K stocks were generally within 18-75 kg ha^{-1} and 120-300 kg ha^{-1}, respectively estimated to be the average levels agronomically adequate for crop growth (Defoer *et al.*, 2000).

Table: 6.3. Soil nutrients stocks in the rooting zone* of the soil

Treatments	N stock (kg ha^{-1})	Extractable P stock (kg ha^{-1})	Exchangeable K stock (kg ha^{-1})
Control (No mineral fertilizer, no manure)	562.3 ± 66	12.3 ± 2	165.5 ± 33
0 g mineral fertilizer + 100 g manure hill^{-1}	629.4 ± 67	21.9 ± 5	257.5 ± 55
0 g mineral fertilizer + 200 g manure hill^{-1}	655.4 ± 66	20.5 ± 5	243.4 ± 61
0 g mineral fertilizer + 300 g manure hill^{-1}	682.7 ± 64	22.5 ± 5	265.0 ± 58
2 g DAP hill^{-1} + 0 g manure hill^{-1}	614.4 ± 72	25.8 ± 8	196.2 ± 36
2 g DAP hill^{-1} + 100 g manure hill^{-1}	633.4 ± 74	36.1 ± 8	242.2 ± 40
2 g DAP hill^{-1} + 200 g manure hill^{-1}	626.5 ± 62	27.0 ± 6	281.0 ± 66
2 g DAP hill^{-1} + 300 g manure hill^{-1}	648.1 ± 62	41.1 ± 5	289.1 ± 70
6 g NPK hill^{-1} + 0 g manure hill^{-1}	617.2 ± 46	30.5 ± 3	257.3 ± 70
6 g NPK hill^{-1} + 100 g manure hill^{-1}	594.7 ± 72	30.6 ± 7	219.2 ± 43
6 g NPK hill^{-1} + 200 g manure hill^{-1}	675.6 ± 84	22.5 ± 8	289.4 ± 70
6 g NPK hill^{-1} + 300 g manure hill^{-1}	695.2 ± 82	47.7 ± 7	278.4 ± 55

* rooting zone refers to the soil layer where most of the roots are concentrated; ± Standard error

6.3.2. Millet grain and straw yields

The grain and straw yields recorded in 2013 and 2014 are presented in Table 6.4. The grain yields ranged from 106 to 852 kg ha^{-1} in 2013. These grain yields were lower than those produced in 2014 which ranged from 607 to 1875 kg ha^{-1}. There were significant differences ($P < 0.05$) in grain yield among the treatments in both years. The lowest grain yield was recorded in the control treatment. The plots that received the combined application of fertilizer micro-dosing and manure, produced the highest grain yields. Basically, a similar trend was observed for the data on the straw yields. The highest straw yields were recorded in the plots that received combined application of fertilizer micro-dosing treatments with manure regardless of manure rates applied. Conversely, the lowest straw yield was obtained in control plots (without mineral fertilizer and manure).

Table: [1].4. Grain and straw yields recorded in 2013 and 2014

Treatments	2013		2014	
	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})

[1] .3.3. Nutrients flows

Table 6.5 summarises the nutrient inputs applied in the current study. Manure (IN2) was the main input of N, P and K among all the inflows. Although, the same rates of manure (1000 kg ha^{-1}, 2000 kg ha^{-1}, and 3000 kg ha^{-1}) were applied in 2013 and 2014 rainy seasons, the N inputs supplied by manure in 2014 were higher than those of 2013. However, the highest P and K inputs were supplied by manure in 2013. The rainfall and dry depositions (IN3) brought a high quantity of potassium in comparison to that applied through mineral fertilizer (INT1). The contribution of non-symbiotic N fixation was estimated to be 2.7 kg N ha^{-1} and 3.1 kg N ha $^{-1}$ in 2013 and 2014, respectively. Nutrients outputs are presented in Table 6.6. Nutrients export from crop residue (OUT2) were on average 28 kg N ha^{-1}, 2.0 kg P ha^{-1}, and 40 kg K ha^{-1} in 2013. The highest nutrients export from crop residue was recorded in 2014 (36 kg N ha^{-1}, 6.2

Control	106±20	563±36	607±112	2000±314
0 g mineral fertilizer + 100 g manure hill^{-1}	185±38	792±42	999±79	3458±463
0 g mineral fertilizer + 200 g manure hill^{-1}	325±34	1000±115	1019±65	4167±300
0 g mineral fertilizer + 300 g manure hill^{-1}	548±47	1000±144	1337±86	4833±210
2 g DAP hill^{-1} + 0 g manure hill^{-1}	354±90	1000±72	876±36	2792±216
2 g DAP hill^{-1} + 100 g manure hill^{-1}	517±73	1438±108	1431±162	3944±242
2 g DAP hill^{-1} + 200 g manure hill^{-1}	790±62	1667±150	1503±105	4014±251
2 g DAP hill^{-1} + 300 g manure hill^{-1}	802±87	1958±102	1875±262	5278±174
6 g NPK hill^{-1} + 0 g manure hill^{-1}	237±37	750±43	753±91	2750±181
6 g NPK hill^{-1} + 100 g manure hill^{-1}	459±62	1233±41	1399±191	3014±174
6 g NPK hill^{-1} + 200 g manure hill^{-1}	499±16	1333±166	1449±152	3528±201
6 g NPK hill^{-1} + 300 g manure hill^{-1}	852±63	2125±188	1441±188	3194±324
F.pr	*0.022*	*0.013*	*< 0.001*	*< 0.001*
CV (%)	*24.9*	*28.8*	*20.5*	*17.2*
LSD (0.05)	*85*	*295*	*105*	*506*

± Standard error

kg P ha^{-1}, and 49.6 kg K ha^{-1}). The nutrients transferred through crop residue were greater than those from grain yields (OUT1). Nutrients losses through leaching (OUT3) and erosion (OUT5) were the main sources of nutrients export (N and P) among the outputs indirectly measured. Generally, crop residue (OUT2), leaching losses (OUT3) and wind erosion (OUT5) were the major sources of nutrient removal in the current study.

6.3.4. Partial nutrient balances

The partial nutrient balances (IN1 + IN2 – OUT1 – OUT2) in 2013 and 2014 are presented in Table 6.7. On average, the partial nutrients balances were -37.2 kg N ha^{1} yr^{-1}, -1.2 kg P ha^{-1} yr^{-1}, -34.4 kg K ha^{-1} yr^{-1} in plots that received the application of 2 g DAP hill^{-1} and -30.9 kg N ha^{-1} yr^{-1}, -1.1 kg P ha^{-1} yr^{-1}, -27.4 kg K ha^{-1} yr^{-1} for application of 6 g NPK hill^{-1}. The N and K partial balances recorded in fertilizer microdosing treatments were greater than those obtained in the control plots (23.6 kg N ha^{1} yr^{-1} and 20.9 kg K ha^{-1} yr^{-1}).

In 2013, the partial nutrient balance of N was negative in all the treatments. The P partial balances were positive in all the amended plots while K partial balance showed negative trend for the applied nutrients excluding the plots that received lone application of 200 g manure hill^{-1} and 300 g manure hill^{-1}. The differences in partial nutrient balances among the treatments were significant ($P < 0.05$). Similarly, in 2014, the partial nutrient balances for N, P and K were negative in all the treatments except in the plots that received the application of 6 g NPK hill^{-1}+ 200 g manure hill^{-1} or 6 g NPK hill^{-1} + 300 g manure hill^{-1} where the partial P balances were + 0.6 kg P ha^{-1} yr^{-1} and 3.3 kg P ha^{-1} yr^{-1}, respectively.

Table: 6.5. Nutrient inputs used in the current study

2013	IN1[1]			IN2			IN3			IN4
Treatments	N	P	K	N	P	K	N	P	K	N
				kg ha^{-1} yr^{-1}						
Control (No mineral fertilizer, no manure)	0.0	0.0	0.0	0.0	0.0	0.0	6.9	1.3	17.0	2.7
0 g mineral fertilizer + 100 g manure $hill^{-1}$	0.0	0.0	0.0	9.8	3.7	16.0	6.9	1.3	17.0	2.7
0 g mineral fertilizer + 200 g manure $hill^{-1}$	0.0	0.0	0.0	19.6	7.4	32.0	6.9	1.3	17.0	2.7
0 g mineral fertilizer + 300 g manure $hill^{-1}$	0.0	0.0	0.0	29.4	11.1	48.0	6.9	1.3	17.0	2.7
2 g DAP $hill^{-1}$ + 0 g manure $hill^{-1}$	3.6	4.0	0.0	0.0	0.0	0.0	6.9	1.3	17.0	2.7
2 g DAP $hill^{-1}$ + 100 g manure $hill^{-1}$	3.6	4.0	0.0	9.8	3.7	16.0	6.9	1.3	17.0	2.7
2 g DAP $hill^{-1}$ + 200 g manure $hill^{-1}$	3.6	4.0	0.0	19.6	7.4	32.0	6.9	1.3	17.0	2.7
2 g DAP $hill^{-1}$ + 300 g manure $hill^{-1}$	3.6	4.0	0.0	29.4	11.1	48.0	6.9	1.3	17.0	2.7
6 g NPK $hill^{-1}$ + 0 g manure $hill^{-1}$	9.0	3.9	7.5	0.0	0.0	0.0	6.9	1.3	17.0	2.7
6 g NPK $hill^{-1}$ + 100 g manure $hill^{-1}$	9.0	3.9	7.5	9.8	3.7	16.0	6.9	1.3	17.0	2.7
6 g NPK $hill^{-1}$ + 200 g manure $hill^{-1}$	9.0	3.9	7.5	19.6	7.4	32.0	6.9	1.3	17.0	2.7
6 g NPK $hill^{-1}$ + 300 g manure $hill^{-1}$	9.0	3.9	7.5	29.4	11.1	48.0	6.9	1.3	17.0	2.7
2014										
Control (No mineral fertilizer, no manure)	0.0	0.0	0.0	0.0	0.0	0.0	7.5	1.5	17.4	3.1
0 g mineral fertilizer + 100 g manure $hill^{-1}$	0.0	0.0	0.0	15.0	2.8	7.2	7.5	1.5	17.4	3.1
0 g mineral fertilizer + 200 g manure $hill^{-1}$	0.0	0.0	0.0	30.0	5.6	14.4	7.5	1.5	17.4	3.1
0 g mineral fertilizer + 300 g manure $hill^{-1}$	0.0	0.0	0.0	45.0	8.4	21.6	7.5	1.5	17.4	3.1
2 g DAP $hill^{-1}$ + 0 g manure $hill^{-1}$	3.6	4.0	0.0	0.0	0.0	0.0	7.5	1.5	17.4	3.1
2 g DAP $hill^{-1}$ + 100 g manure $hill^{-1}$	3.6	4.0	0.0	15.0	2.8	7.2	7.5	1.5	17.4	3.1

[1] See Table 6.2 for explanation of codes

2 g DAP $hill^{-1}$ + 200 g manure $hill^{-1}$	3.6	4.0	0.0	30.0	5.6	14.4	7.5	1.5	17.4	3.1
2 g DAP $hill^{-1}$ + 300 g manure $hill^{-1}$	3.6	4.0	0.0	45.0	8.4	21.6	7.5	1.5	17.4	3.1
6 g NPK $hill^{-1}$ + 0 g manure $hill^{-1}$	9.0	3.9	7.5	0.0	0.0	0.0	7.5	1.5	17.4	3.1
6 g NPK $hill^{-1}$ + 100 g manure $hill^{-1}$	9.0	3.9	7.5	15.0	2.8	7.2	7.5	1.5	17.4	3.1
6 g NPK $hill^{-1}$ + 200 g manure $hill^{-1}$	9.0	3.9	7.5	30.0	5.6	14.4	7.5	1.5	17.4	3.1
6 g NPK $hill^{-1}$ + 300 g manure $hill^{-1}$	9.0	3.9	7.5	45.0	8.4	21.6	7.5	1.5	17.4	3.1

Table: 6.6. Nutrient outputs used in the current study

2013	OUT1[1]			OUT2			OUT3		OUT4	OUT5		
Treatments	N	P	K	N	P	K	N	K	N	N	P	K
						kg ha^{-1} yr^{-1}						
Control (No mineral fertilizer, no manure)	2.5	0.3	0.4	13.1	0.8	13.6	18.7	0.1	0.5	11.0	7.1	5.4
0 g mineral fertilizer + 100 g manure $hill^{-1}$	4.1	0.6	0.8	18.2	1.4	31.3	19.3	8.9	1.7	11.0	7.1	5.4
0 g mineral fertilizer + 200 g manure $hill^{-1}$	6.8	1.1	1.1	18.1	1.4	21.5	20.5	17.6	3.0	11.0	7.1	5.4
0 g mineral fertilizer + 300 g manure $hill^{-1}$	11.5	1.7	2.4	18.7	1.5	25.4	21.4	26.4	4.3	11.0	7.1	5.4
2 g DAP $hill^{-1}$ + 0 g manure $hill^{-1}$	7.9	1.0	1.2	21.9	1.4	33.6	16.9	0.1	0.9	11.0	7.1	5.4
2 g DAP $hill^{-1}$ + 100 g manure $hill^{-1}$	11.6	1.8	2.1	33.1	2.9	60.6	16.0	8.9	2.2	11.0	7.1	5.4
2 g DAP $hill^{-1}$ + 200 g manure $hill^{-1}$	16.9	2.2	2.3	34.4	2.9	43.7	16.6	17.6	3.5	11.0	7.1	5.4
2 g DAP $hill^{-1}$ + 300 g manure $hill^{-1}$	19.0	2.8	3.4	40.6	3.0	67.5	16.9	26.4	4.8	11.0	7.1	5.4
6 g NPK $hill^{-1}$ + 0 g manure $hill^{-1}$	5.7	0.7	0.7	22.3	1.4	23.1	18.1	4.2	1.6	11.0	7.1	5.4
6 g NPK $hill^{-1}$ + 100 g manure $hill^{-1}$	10.2	1.4	1.6	27.0	1.8	40.0	18.3	13.0	2.9	11.0	7.1	5.4
6 g NPK $hill^{-1}$ + 200 g manure $hill^{-1}$	9.4	1.6	1.6	22.7	1.9	38.8	20.9	21.7	4.2	11.0	7.1	5.4
6 g NPK $hill^{-1}$ + 300 g manure $hill^{-1}$	19.4	2.5	2.9	50.6	3.6	78.3	16.1	30.5	5.5	11.0	7.1	5.4
2014												

[1] See Table 6.2 for explanation of codes

Control (No mineral fertilizer, no manure)	13.3	2.3	5.3	18.2	2.5	22.4	10.4	0.1	0.6	11.0	7.1	5.4
0 g mineral fertilizer + 100 g manure hill^{-1}	21.3	4.8	8.0	39.3	6.8	50.1	6.5	4.5	2.6	11.0	7.1	5.4
0 g mineral fertilizer + 200 g manure hill^{-1}	22.3	5.9	9.6	33.9	5.8	44.3	9.0	8.9	4.5	11.0	7.1	5.4
0 g mineral fertilizer + 300 g manure hill^{-1}	28.3	6.8	11.4	48.1	9.1	61.1	10.4	13.3	6.5	11.0	7.1	5.4
2 g DAP hill^{-1} + 0 g manure hill^{-1}	19.1	3.3	6.6	32.6	4.5	27.4	4.3	0.1	1.1	11.0	7.1	5.4
2 g DAP hill^{-1} + 100 g manure hill^{-1}	34.3	8.9	14.3	41.7	6.3	89.2	1.9	4.5	3.1	11.0	7.1	5.4
2 g DAP hill^{-1} + 200 g manure hill^{-1}	32.9	9.0	13.5	34.7	6.8	38.8	9.1	8.9	5.0	11.0	7.1	5.4
2 g DAP hill^{-1} + 300 g manure hill^{-1}	40.3	9.2	14.5	49.3	10.2	69.7	5.8	13.3	7.0	11.0	7.1	5.4
6 g NPK hill^{-1} + 0 g manure hill^{-1}	18.3	3.4	6.4	33.4	4.5	39.2	4.9	4.7	1.8	11.0	7.1	5.4
6 g NPK hill^{-1} + 100 g manure hill^{-1}	30.3	7.3	12.3	26.7	4.6	29.9	10.7	9.1	3.8	11.0	7.1	5.4
6 g NPK hill^{-1} + 200 g manure hill^{-1}	31.8	7.7	11.9	37.4	6.3	45.9	10.1	13.5	5.7	11.0	7.1	5.4
6 g NPK hill^{-1} + 300 g manure hill^{-1}	29.4	7.7	13.0	54.4	6.4	77.7	17.5	17.8	7.7	11.0	7.1	5.4

Table: 6.7. Effect of fertilizer micro-dosing and manure application on partial nutrient balances

Treatments	2013 N	2013 P	2013 K	2014 N	2014 P	2014 K
	kg ha^{-1} yr^{-1}					
Control	-15.6	-1.0	-14.0	-31.5	-4.8	-27.7
0 g mineral fertilizer + 100 g manure hill^{-1}	-12.5	+1.7	-16.1	-45.6	-8.8	-50.9
0 g mineral fertilizer + 200 g manure hill^{-1}	-5.3	+4.9	+9.4	-26.2	-6.1	-39.5
0 g mineral fertilizer + 300 g manure hill^{-1}	-0.8	+7.9	+20.2	-31.4	-7.5	-50.9
2 g DAP hill^{-1} + 0 g manure hill^{-1}	-26.2	+1.6	-34.8	-48.1	-3.9	-34.0
2 g DAP hill^{-1} + 100 g manure hill^{-1}	-31.3	+3.1	-46.7	-57.4	-8.5	-96.3
2 g DAP hill^{-1} + 200 g manure hill^{-1}	-28.1	+6.3	-14.0	-34.0	-6.3	-37.9
2 g DAP hill^{-1} + 300 g manure hill^{-1}	-26.6	+9.2	-22.9	-41.0	-7.1	-62.6
6 g NPK hill^{-1} + 0 g manure hill^{-1}	-19.0	+1.8	-16.4	-42.7	-4.0	-38.1

6 g NPK hill^{-}+ 100 g manure hill^{-1}	-18.4	+4.5	-18.1	-33.0	-0.1	-27.6
6 g NPK hill^{-}+ 200 g manure hill^{-1}	-3.5	+7.9	-0.9	-30.2	0.6	-35.9
6 g NPK hill^{-}+ 300 g manure hill^{-1}	-31.6	+8.9	-25.7	-16.8	3.3	-61.7
F.pr	*0.009*	*0.024*	*0.020*	*0.023*	*< 0.001*	*0.002*
CV (%)	*29.5*	*23.3*	*24.6*	*29.5*	*32.8*	*36.2*
SED (±)	*3.14*	*0.97*	*5.23*	*3.16*	*1.11*	*5.62*

SED = Standard errors of differences of means

6.3.5. Full nutrient balance and nutrient stock: balance (NSB) ratio

Table 6.8 provides the full nutrient balances. In 2013, N balances were negative for all the treatments and ranged from -27.8 kg ha^{-1} yr^{-1} to – 54.5 kg ha^{-1} yr^{-1}. The balances for P were positive only on the plots that received the application of micro-dosing treatments combined either with 200 g manure $hill^{-1}$ or 300 g manure $hill^{-1}$. Potassium (K) balances were negative for all treatments, except for sole application of 200 g manure $hill^{-1}$ and 300 g manure $hill^{-1}$ where positive balances were observed to be + 3.4 kg ha^{-1} yr^{-1} and + 5.4 kg ha^{-1} yr^{-1}, respectively.

In 2014, the balances of N, P and K were negative in all the treatments. The full N balance ranged from -40.2 kg ha^{-1} yr^{-1} to -62.7 kg ha^{-1} yr^{-1}, while the full balances of P varied from -2.3 kg ha^{-1} yr^{-1} to - 14.4 kg ha^{-1} yr^{-1} and full K balances ranged from - 15.8 kg ha^{-1} yr^{-1} to - 88.8 kg ha^{-1} yr^{-1}. There were significant differences in full nutrients balances among the treatments ($P < 0.05$).

On average, the annual nutrient losses ranged from -38.2 kg ha^{-1} to -56.8 kg ha^{-1} for N, -1.5 kg ha^{-1} to -9.2 kg ha^{-1} for P while K losses varied from -9.1 kg ha to -66.4 kg ha^{-1} (Table 6.10). However, the highest N (-56.8 kg ha^{-1} yr^{-1}) and K (-66.4 kg ha^{-1} yr^{1}) losses were recorded with 2 g DAP $hill^{-1}$ + 100 g manure $hill^{-1}$. The annual losses of nutrients under fertilizer micro-dosing treatments were on average – 47 kg N ha^{-1} yr^{-1}, -7 kg P ha^{-1} yr^{-1} and -21 kg K ha^{-1} yr^{-1} which represented 7%, 24% and 10% of N, P and K stocks, respectively. These nutrients losses in fertilizer micro-dosing plots were greater than those recorded in control plots where no inputs were added (Table 6.10).

The nutrient stock to balance ratio (NSB) in 2013 ranged from 13 to 25 for nitrogen, 2 to 48 for P and 6 to 67 for K (Table 6.9). These NSB ratios decreased markedly in

2014 and ranged from 10 to 16 for N, 1 to 21 for P and 4 to 10 for K. The application of fertilizer micro-dosing plots alone recorded the lowest NSB ratio for N compared to control plots.

Table: 6.8. Effect of fertilizer micro-dosing and manure on full nutrient balances

Treatments	2013 N	2013 P	2013 K	2014 N	2014 P	2014 K
	kg ha^{-1} yr^{-1}					
Control	-36.2	-6.8	-2.5	-42.9	-10.4	-15.8
0 g mineral fertilizer + 100 g manure hill^{-1}	-34.9	-4.1	-13.3	-55.1	-14.4	-43.4
0 g mineral fertilizer + 200 g manure hill^{-1}	-30.2	-0.9	+3.4	-40.2	-11.7	-36.4
0 g mineral fertilizer + 300 g manure hill^{-1}	-27.8	+2.2	+5.4	-48.6	-13.2	-52.1
2 g DAP hill^{-1} + 0 g manure hill^{-1}	-45.4	-4.2	-23.3	-54.0	-9.5	-22.1
2 g DAP hill^{-1} + 100 g manure hill^{-1}	-51.0	-2.7	-44.0	-62.7	-14.1	-88.8
2 g DAP hill^{-1} + 200 g manure hill^{-1}	-49.6	+0.6	-20.0	-48.5	-11.9	-34.8
2 g DAP hill^{-1} + 300 g manure hill^{-1}	-49.7	+3.5	-37.7	-54.2	-12.7	-63.9
6 g NPK hill^{-}+ 0 g manure hill^{-1}	-40.1	-4.0	-9.0	-49.9	-9.7	-30.8
6 g NPK hill^{-}+ 100 g manure hill^{-1}	-41.0	-1.3	-19.5	-47.8	-5.7	-24.6
6 g NPK hill^{-}+ 200 g manure hill^{-1}	-30.0	+2.1	-11.1	-46.4	-5.0	-37.4
6 g NPK hill^{-}+ 300 g manure hill^{-1}	-54.5	+3.1	-44.6	-42.3	-2.3	-67.5
F.pr	*0.023*	*0.029*	*0.021*	*0.035*	*< 0.001*	*0.002*
CV (%)	*27.6*	*21.9*	*32.1*	*20.6*	*31.9*	*29.9*
SED (±)	*2.6*	*0.97*	*4.9*	*1.8*	*1.1*	*6.2*

SED = Standard errors of differences of means

The NSB ratios for P were 6 and 8 in 2013 for the plots that received the applications of 2 g DAP hill^{-1} + 0 g manure hill^{-1} and 6 g NPK hill^{-1} + 0 g manure hill^{-1}, respectively. The NSB ratios dropped to 3 for the same treatments in 2014. The NSB ratios for K of the sole application of 2 g DAP hill^{-1} were 8 and 9 in 2013 and 2014, respectively. For the plots that received sole application of 6 g NPK hill^{-1}, the NSB ratios were 29 and 8 in 2013 and 2014, respectively. The application of fertilizer micro-dosing along with manure offered the highest NSB for P. The greater value of NSB for P was estimated to be 48 and was obtained in the plots that received the application of 2 g

DAP hill^{-1} + 200 g manure hill^{-1} in 2013 while the highest value of NSB ratio for P of 21 was recorded by 6 g NPK hill^{-1} + 300 g manure hill^{-1} in 2014 (Table 6.9).

Unlike N, there was a marked decrease in NSB ratio for K when fertilizer micro-dosing rates were applied together with manure (Table 6.9). However, the decrease in NSB ratio for K appeared to be higher in the plots that received application of manure exclusively in 2014. On average the NSB ratios for N were 12 and 14 for the plots that received the sole applications of 2 g DAP hill^{-1} and 6 g NPK hill^{-1} (Table 6.10). The NSB ratios for P did not exceed 5 for the fertilizer micro-dosing plots (2 g DAP hill^{-1} and 6 g NPK hill^{-1}). The NSB ratio for K was 19 with the application of 6 g NPK hill^{1} and decreased to 9 for the plots that received lone application of 2 g DAP hill^{-1}. Generally, the NSB ratios for K were lower in the plots where DAP fertilizer was applied compared with the plots that received the application of NPK fertilizer (Table 6.10).

Table: 6.9. Effect of fertilizer micro-dosing and manure on nutrient stock: balance ratios

	2013			2014		
Treatments	N	P	K	N	P	K
Control	16	2	67	13	1	10
0 g mineral fertilizer + 100 g manure hill^{-1}	18	5	19	11	2	6
0 g mineral fertilizer + 200 g manure hill^{-1}	22	23	72	16	2	7
0 g mineral fertilizer + 300 g manure hill^{-1}	25	10	49	14	2	5
2 g DAP hill^{-1} + 0 g manure hill^{-1}	14	6	8	11	3	9
2 g DAP hill^{-1} + 100 g manure hill^{-1}	12	13	6	10	3	3
2 g DAP hill^{-1} + 200 g manure hill^{-1}	13	48	14	13	2	8
2 g DAP hill^{-1} + 300 g manure hill^{-1}	13	12	8	12	3	5
6 g NPK hill^{-1} + 0 g manure hill^{-1}	15	8	29	12	3	8
6 g NPK hill^{-1} + 100 g manure hill^{-1}	15	23	11	12	5	9
6 g NPK hill^{-1} + 200 g manure hill^{-1}	23	11	26	15	4	8
6 g NPK hill^{-1} + 300 g manure hill^{-1}	13	15	6	16	21	4

Table: 6. 10. Average annual full nutrient and nutrient stock: balance ratio

Treatments	Average annual nutrient full balance			Average nutrient stock: balance ratio		
	N	P	K	N	P	K
	kg ha^{-1} yr^{-1}					
Control	-39.6	-8.6	-9.1	14	1	39
0 g mineral fertilizer + 100 g manure $hill^{-1}$	-45.0	-9.2	-28.4	15	3	13
0 g mineral fertilizer + 200 g manure $hill^{-1}$	-35.2	-6.3	-16.5	19	12	39
0 g mineral fertilizer + 300 g manure $hill^{-1}$	-38.2	-5.5	-23.4	19	6	27
2 g DAP $hill^{-1}$ + 0 g manure $hill^{-1}$	-49.7	-6.9	-22.7	12	4	9
2 g DAP $hill^{-1}$ + 100 g manure $hill^{-1}$	-56.8	-8.4	-66.4	11	8	4
2 g DAP $hill^{-1}$ + 200 g manure $hill^{-1}$	-49.1	-5.7	-27.4	13	25	11
2 g DAP $hill^{-1}$ + 300 g manure $hill^{-1}$	-51.9	-4.6	-50.8	13	8	6
6 g NPK $hill^{-1}$ + 0 g manure $hill^{-1}$	-45.0	-6.9	-19.9	14	5	19
6 g NPK $hill^{-1}$ + 100 g manure $hill^{-1}$	-44.4	-3.5	-22.0	13	14	10
6 g NPK $hill^{-1}$ + 200 g manure $hill^{-1}$	-38.2	-1.5	-24.2	19	8	17
6 g NPK $hill^{-1}$ + 300 g manure $hill^{-1}$	-48.4	+0.4	-56.0	15	18	5

6.4. Discussion

The main objective of this study was to assess the effect of fertilizer micro-dosing on soil nutrient depletion. The partial balance for N was negative in both years while an accumulation of P was observed in 2013 for all the plots except in control plots. However, in 2014, the partial P balance was negative in all the treatments excluding those that received the application of 6 g NPK $hill^{-1}$ combined with manure either at 200 g $hill^{-1}$ or 300 g $hill^{-1}$ application rates (Table 6.7). The positive partial balance for P documented in these treatments can be attributed to the relatively low P uptake by the plant in these treatments as compared to P applied. The N partial balances of lone application of fertilizer micro-dosing ranged from -26 to - 48 kg ha^{-1} yr^{-1} for 2 g DAP $hill^{-1}$ and -19 to -43 kg $ha^{-1}yr^{-1}$ for 6 g NPK $hill^{-1}$. These N values were higher than the average net N mining estimated to be 15 kg ha^{-1} yr^{-1}, for the traditional fields planted to pearl millet in the southern Sahel (Buerkert and Hiernaux, 1998). The results of this study indicated that the grain and straw yields of 350 kg ha^{-1} and 1000 kg ha^{-1}, respectively led to N depletion of 26 kg ha^{-1} yr^{-1} under fertilizer micro-dosing. This value is within the range of 13 to 56 kg N $ha^{-1}yr^{-1}$ losses reported by Ibrahim *et al.* (2014) with the application of 2 g DAP $hill^{-1}$. The K partial balance showed a negative balance in all the plots that received sole application of fertilizer micro-dosing. The depletion of K was more intense in the plots with DAP application where no K input was applied. The implication is that the native K could serve as the main source of K uptake when diammonium phosphate was used as nutrient source. Although, the K stock was within the average level (120-300 kg ha^{-1}) set by Defoer *et al.* (2000), continuous cropping without replenishing will lead to the depletion of this stock. The partial balances of N, P and K, showed a greater soil nutrients depletion in 2014 compared with 2013 as a result of the higher yields recorded (Table 6.4). The difference in grain yields could be attributed to the inter-annual rainfall variability observed between the rainy seasons (475 mm in 2013 vs. 695 mm in 2014) in the study area where dry spells during the cropping seasons are common occurrences (Sivakumar and Salaam, 1999). This inter-annual yields difference could be also explained by the difference in quality of manure applied; more N input was supplied through manure in 2014 compared with that supplied in 2013 (Table 6.5). In both years, the partial nutrients balances were exacerbated by the straw yields produced (OUT2) which accounted for on average 66% N, 55% P and 89% K losses. Although, crop residues were an important source of nutrient removal, most of the studies that dealt with nutrient depletion under fertilizer micro-dosing (Buerkert and Schlecht, 2013; Aune and Coulibaly, 2015), did not consider the quantity of nutrients removed through crop residue. It, was observed that nutrient accumulated in grain yield which exceeds 570 kg ha^{-1} led to nutrients imbalance under fertilizer micro-dosing treatments (Table 6.7). The grain yields of pearl millet reported in fertilizer micro-dosing technology, on sandy soils across a broad range of climatic and soil conditions in West Africa ranged from 547 to 577 kg ha^{-1} (Bagayoko *et al.*, 2011). It appears that adding the quantity of nutrients removed from crop residue to the reported levels of grain yields will negatively affect the partial nutrient balance.

The full nutrient balance profile indicates a considerable N, P and K depletion with lone application of fertilizer micro-dosing (Table 6.8). The average annual nutrient losses under fertilizer micro-dosing treatments ranged from -45 to -50 kg N ha^{-1}, -6.8 kg P ha^{-1} and -23 to -20 kg K ha^{-1} (Table 6.10). These values accounted for 7%, 24% and 10% of N, P and K stocks. The nutrients depletion recorded from the fertilizer micro-dosing plots show that the quantity of nutrients applied through this technology was not adequate to meet crop requirement for crop biomass production. Several studies have indicated that the negative nutrient balance does not necessarily imply the threat of soil nutrient depletion through nutrient mining (Bindraban *et al.*, 2000; Vanlauwe and Giller, 2006). However, this holds particularly when soil nutrient stock is large and able to cushion negative nutrient balances. In a situation such as that of the study area where the soil nutrients stock levels are not high enough (Table 6.3), crop production could not be sustained for long. According to Hilhorst *et al.* (2000), agricultural practice with an annual stock decline for total nitrogen of more than 1 % was considered not sustainable which was found under fertilizer micro-dosing practice where an average annual full N balance accounted for 7 % of N stock. It thus appears that fertilizer micro-dosing may not be ecologically friendly because the high productivity relies mainly on the soil native nutrients.

The nutrient stock to balance ratio (NSB) which provides an indication of how long farming can continue in the same way, given the available nutrients (Defoer *et al.*, 2000), decreased markedly from 2013 to 2014 (Table 6.9). On average, the NSB ratio ranged from 12 to 14 for N in the plots that received sole applications of fertilizer micro-dosing. This implies that under the current fertilizer micro-dosing practice, crop yields could be sustained for only 12 to 14 years before lessening the soil N stock (Table 6.10). The situation is even worse in NSB ratios for P and K. The NSB for P did not exceed 4, indicating that the P stock sustains crop production for just 4 years with the current level of yields (Table 6.4). These results indicate that if the stocks of available nutrients are not large, such as in the case of Sahelian sandy soils where soils are most low to moderate inherent soil fertility (Bationo *et al.*, 1998a), the fertilizer micro-dosing could not support sustainable yields. The results obtained in the current study suggest that for the small-holder farmers, fertilizer micro-dosing technology should be considered a as just a stopgap option.

Generally, application of mineral fertilizer along with organic amendment increases nutrients availability for the plant and thereby increases crop yields. In this study, combined application of fertilizer micro-dosing and manure significantly increased millet yields which led to an increase in nutrient uptake. The combined use of mineral fertilizer and manure generated a favorable soil physical conditions and an increase in crop nutrients availability which resulted in high dry matter production (Abd ElLattief, 2011). Increase in crop yield leads to greater soil nutrients extraction which eventually leads to the greater soil nutrients depletion (Vanlauwe and Giller, 2006). Both partial and full balances for N, P and K were negative in all treatments (Table 6.7 and 5.8). However, the plots that received the combined application of fertilizer microdosing with manure either at 200 g hill^{-1} or 300 g hill^{-1} application rates exhibited positive P balance in 2013 due to the low level of yields recorded.

4.5. Conclusion

The partial and full balances of nutrient obtained in this study indicated that fertilizer micro-dosing increases the risk of soil nutrients losses in low input-millet based cropping system. Combined application of fertilizer micro-dosing and manure was not able to balance the nutrients exported by the obtained yields. The export of nutrients from crop residue was found to exacerbate the nutrients depletion. Retaining crop residues in the fields could therefore influence reversing the potential soil mining effect of fertilizer micro-dosing technology. It is therefore, suggested that for sustained crop production under fertilizer micro-dosing technology, recycling of crop residues must be considered in low input millet-based cropping system. Long-term study is, however, recommended to establish the long-term impact of fertilizer micro-dosing on nutrient mining.

Chapter Seven

Acacia tumida mulch and fertilizer micro-dosing increase millet yield and water use efficiency in Sahelian semi-arid environment

Re-submitted to *Nutrient Cycling in Agroecosystems* as:

Ali Ibrahim, Robert Clement Abaidoo, Fatondji Dougbedji and Andrews Opoku. Integrated use of *Acacia tumida* mulch and fertilizer micro-dosing increases millet yield and water use efficiency in Sahelian semi-arid environment

Chapter Seven

7. *Acacia tumida* mulch and fertilizer micro-dosing increase millet yield and water use efficiency in Sahelian semi-arid environment

Abstract

Limited availability of soil organic amendments and unpredictable rainfall, decrease crop yields drastically in the Sahel. There is, therefore, a need to develop an improved technology for conserving soil moisture and enhancing crop yields in the Sahelian semi-arid environment. A two-year field experiment was conducted to investigate the mulching effects of *Acacia tumida* pruning relative to commonly applied organic materials in Niger on millet growth, yields and water use efficiency (WUE) under fertilizer micro-dosing technology. We hypothesized that (1) *Acacia tumida* pruning is a suitable mulching alternative for crop residues in the biomass-scarce areas of Niger and (2) combined application of *Acacia tumida* mulch and fertilizer micro-dosing increases millet yield and water use efficiency. Two fertilizer micro-dosing options (20 kg DAP ha^{-1}, 60 kg NPK ha^{-1}) and three types of organic mulches (millet straw, *Acacia tumida* mulch, and manure) and the relevant control treatments were arranged in factorial experiment organized in a randomized complete block design with four replications. Fertilizer micro-dosing increased millet grain yield on average by 28%. This millet grain yield increased further by 37% with combined application of fertilizer micro-dosing and organic mulch. Grain yield increases relative to the un-mulched control were 51% for manure, 46% for *Acacia tumida* mulch and 36% for millet mulch. Leaf area index (LAI) and root length density (RLD) were also greater under mulched plots. Fertilizer micro-dosing increased water use efficiency (WUE) of millet on average by 24%, while the addition of *Acacia tumida* pruning, manure and millet increased WUE on average 55%, 49% and 25%, respectively. We conclude that combined application of micro-dosing and organic mulch is an effective fertilization strategy to enhance millet yield and water use efficiency in low-input cropping system and that *Acacia tumida* pruning could serve as an appropriate mulching alternative for further increasing crop yields and water use efficiency in the biomass-scarce and drought prone environment such as the Sahel. However, the economic and social

implications and the long-term agronomic effects of this agroforestry tree in Sahelian millet based system have to be explored further.

Keywords: Organic mulch, fertilizer micro-dosing, *Acacia tumida*, millet yield, water use efficiency

7.1. Introduction

Inadequate soil fertility management and irregular rainfall distribution are the most important limiting factors for crop production in Sahelian cropping systems (Bationo *et al.*, 1995; Schlecht *et al.*, 2006). To meet the food requirements of the increasing population in the Sahelian areas there is, the need for enhancing soil fertility potential (Lal, 2006). Accessibility to and affordability of external inputs such as mineral fertilizers limit their use by smallholder farmers (Abdoulaye and Sanders, 2005). Therefore, Sahelian smallholder farmers tend to rely mainly on organic amendments such as crop residues and animal manure, which are the most accessible nutrient sources in the Sahelian cereal-based cropping systems. The positive contribution of crop residues in enhancing crop yields has received extensive consideration (Bationo *et al.*, 1993; Rebafka *et al.*, 1994; Buerkert *et al.*, 2002; Yamoah *et al.*, 2002; Turmel *et al.*, 2014). For example, Yamoah *et al.* (2002) reported that return of crop residues into the soil significantly increased millet grain yields, water and fertilizer use efficiencies. Larbi *et al.* (2002) observed that grain yield in maize improved significantly with an increasing amount of crop residues applied as mulch. Larbi *et al.* (2002) also reported that soil organic carbon, total nitrogen and extractable soil phosphorus contents increased by crop residue amendments. The mechanisms underlying the positive effects of crop residue mulches in different agro-ecological West African zones have been explored by Buerkert *et al.* (2000). These authors supported the statement that the positive crop residue effects on weakly buffered

Sahelian soils were due to the enhanced P availability and to the protection of seedlings against wind erosion.

Although, the contribution of crop residues in increasing yields and maintaining soil fertility is evident, the use of this material for crop production purposes in the Sahelian zones is restricted due to the intense competition for use as animals feed, fuel and building material (Bationo *et al*., 1998b; Valbuena *et al*., 2014). Furthermore, the rates of crop residues reported to achieve the beneficial effects are much higher than what is available in smallholder farms (Akponikpè *et al*., 2014). For instance, in Niger the recommended rate of crop residues is around 2,000 kg ha^{-1} $year^{-1}$ (Rebafka *et al*., 1994), while the quantity of millet straw in farmer fields is merely around 1,200 kg ha^{1} (Baidu-Forson, 1995). The implication is that, the recommended amount of crop residue is not accessible for incorporation into the soil or used as mulch, unless the straw production increases dramatically through the application of inorganic fertilizers and the straw is not used as animal feed, fuel and building material (Bationo *et al*., 1995).

Fertilizer micro-dosing has been promoted to increase crop yield and residue production, and the additional crop residue production could be used as mulching material (Aune and Bationo, 2008; Bagayoko *et al*., 2011). However, recent works on millet response to fertilizer micro-dosing technology, indicated that low soil organic matter characterizing the Sahelian sandy soils contributes immensely to the low response of millet yields (Tabo *et al*., 2011). To enhance crop response to fertilizer micro-dosing technology, there is, therefore, a need to supplement it with an organic resource. However, the competing uses of crop residues make their use in agricultural purposes difficult in the Sahel. Furthermore, it is well established that the economic benefits for feeding crop residues to livestock greatly exceeds the economic benefits derived from using crop residues as soil amendments (Opoku, 2011). This makes the use of crop residues as mulching material in the Sahelian zones also a daunting challenge. Consequently a reliable option for resolving the problem of crop residues scarcity in the biomass-scarce dry areas is to identify other sources of organic amendment that can be easily adopted by Sahelian smallholder farmers.

The use of agro-forestry trees for mulching is a possible option for the Sahel (Tilander and Bonzi, 1997). However, the contribution of existing agro-forestry trees as source of mulch has not been well investigated in the Sahelian areas. *Acacia tumida*, is one of the fast growing agro-forestry Australian *Acacias* introduced and tested in Sahelian countries in the early 1980s with the aim to improve food security and combat hunger (Rinaudo *et al.*, 2002). This species produces good seed yields and provides other products and services such as soil fertility improvement through nitrogen fixation and leaves for mulching. The pruning adds organic matter and nutrients to the soil (Rinaudo and Cunningham, 2008). Unlike other agroforestry trees, there is, however, scanty information on the mulching effects of *A. tumida* pruning in low-input smallholder cereal-based cropping systems.

The current study is aimed at establishing the mulching effects of *Acacia tumida* pruning relative to commonly applied organic amendments (millet straw and manure) in Niger on millet growth, yields and water use efficiency under fertilizer micro-dosing technology. We hypothesized that (1) *Acacia tumida* pruning is a suitable mulching alternative for crop residue in the biomass-scarce dry areas of Niger and (2) combined application of *Acacia tumida* mulch and fertilizer micro-dosing further increases millet yield and water use efficiency.

7.2. Materials and methods

7.2.1. Experimental site description

The experiment was set up in the 2013 and 2014 rainy seasons at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Research Station located at Sadoré, Niger (13˚ 15’ N and 2˚ 18’ E, 240 m asl). The trial field had been left as natural fallow for nine years. The soil is classified as a sandy Arenosol (West *et al.*, 1984). The climatic conditions are characterized by a rainy season that takes place between June and September. A dry season dominates the rest of the year. The average annual rainfall for the last thirty years in Sadoré is 551 ± 110 mm (± standard deviation) and the average temperature is 29°C (ICRISAT Climate Database, 19832014).

7.2.2. Experimental design

The experiment was a 3 x 4 factorial experiment organized in randomized complete block design with four replications. The treatments consisted of factorial combinations of three levels of fertilizer micro-dosing and four types of organic mulches. The fertilizer micro-dosing treatments were (i) 20 kg ha^{-1} of diammonium phosphate (DAP, equivalent to 4 kg P ha^{-1} and 3.6 kg N ha^{-1}), (ii) 60 kg ha^{-1} of composite fertilizer NPK 15-15-15 (equivalent to 9 kg N ha^{-1}, 3.93 kg P ha^{-1}, and 7.47 kg K ha^{-1}) and (iii) a control (no fertilizer). The application of these micro-dosing rates corresponded to 2 g DAP $hill^{-1}$ and 6 g NPK $hill^{-1}$, respectively, which are the current fertilizer microdosing rates recommended in the study area (Tabo *et al.*, 2011). Since P is the most limiting soil nutrient in the study area, the DAP and NPK rates applied were estimated to supply equal quantities of P (0.4 g P $hill^{-1}$). Hence these two sources of nutrient are used interchangeably because farmers did not have access to fertilizers at the due time.

Thus, using different sources of nutrients that supplied equivalent quantities of P gave farmers alternatives. The types of organic mulch used were (i) millet straw (ii) *Acacia tumida* mulch (iii) cattle manure and (iv) Control (no organic mulching). All mulches were applied at the recommended rate of 2,000 kg ha^{-1} for crop residue application (Muehlig-Versen *et al.*, 2003). The inorganic fertilizer treatments were applied at sowing while the organic mulching materials were broadcasted after sowing in order to avoid losses through wind. Millet straw and *Acacia tumida* prunings were collected from the ICRISAT Research Station. *Acacia tumida* trees were pruned in May and the prunings were sun-dried before the onset of the rainy season. The manure was collected from a barn in Sadoré village. The initial chemical characteristics of these organic mulches are presented in Table 7.1.

The size of each treatment plot was 7 m x 7 m. Seeds of improved variety of millet, ICMV IS 89305 (110 maturity days) were sown on 27 June 2013 and 1st June 2014 which coincided with the onset of the rainy season. The planting hills were spaced by 1 x 1 m to attain a plant population of 10,000 hills ha^{-1} (current recommended plant density).

Table: 7.1. Initial organic amendment quality

	Total N (%)	Total P (%)	Total K (%)	C/N	Lignin (%)	Polyphenol (%)
2013						
Manure (n = 5)	1.0	0.4	1.6	23	ND	ND
Millet straw (n = 5)	1.7	0.14	1.3	43	ND	ND
Acacia tumida mulch (n= 5)	2.0	0.12	1.3	20	ND	ND
2014						
Manure (n= 5)	1.5	0.34	0.7	29	11.8	0.7
Millet straw (n= 5)	0.8	0.10	1.8	64	7.2	0.6
Acacia tumida mulch (n= 5)	2.3	0.14	1.5	22	22.1	1.3

ND = not determined

The millet was thinned to three plants per hill at 21 days after sowing followed by the first weeding. There were three weeding events during each cropping year. The millet panicles were harvested on 10 October in 2013 and 15 September in 2014 which coincided with the harvest maturity stage. To determine the millet grain yield and the dry matter yield (TDM), straw samples and millet panicles were harvested from the central 5 m x 5 m portion of each plot were oven-dried at 65 °C for 48 h and hand threshed. Thereafter, the samples were weighed and expressed in kg ha^{-1}.

7.2.3. Data collection and analysis

7.2.3.1 Measurement of growth parameters

Leaf area (LA) was measured at tillering, elongation and flowering and dough stage. At each measurement stage, two pearl millet hills were randomly harvested in each treatment. The green leaves were taken to the laboratory for leaf length and width measurements. Leaf length and width were measured with a rule and the LA was determined from the formula used by Ma *et al.* (2013) as follows:

$$\textit{Leaf area (LA)} = \textit{Leaf length} \times \textit{maximum width} \times k \qquad [7.1]$$

where k is a shape factor with the value of 0.5 for partially unfolded leaves and 0.75 for completely unfolded leaves.

The LAI was calculated as the ratio of LA to the surface area of the harvested plot. Root samples were collected at the tillering stage from 0 to 20 cm depth directly under the hill with a metal frame measuring 15 x 10 x 10 cm. Roots were subsequently collected at 20 cm depth increment with an access aluminium tube of 7.5 cm inner diameter following the first sampling depth of 0-20 cm. Sample cores were washed out separately by mixing the sample with tap-water within a plastic pail. The suspension was decanted and root were sieved through a 0.63 mm. Root length (RL) for each sample core was calculated individually then the root length for the two hills in each plot were averaged to obtain root length for each plot. The root length was calculated by determining root intersections (N) using the grid counting method as described in section 3.2.7. The Root length density (RLD) was calculated as follows:

$$RLD\ (cm\ cm^{-3}) = \frac{R}{V} \qquad [7.2]$$

where R is Root length in cm and V is soil volume of corresponding depth in cm^3.

7.2.3.2. Soil moisture measurement

The rainfall data was recorded through a rain gauge placed at the experimental field. Access tubes were installed in each experimental plot (treatment) to monitor weekly soil moisture with a calibrated neutron probe from 0.15 to 2 m depth at 0.15 m intervals. The volumetric water content (Θ_v (%) was calculated with the formula used by Fatondji (2002) as follows:

$$[7.3] \qquad \Theta v = a + b\left(\frac{C}{Cs}\right)$$

where, Θ_v is volumetric water content expressed in %; a is the intercept of the equation of the neutron probe calibration curve; b is the slope of the equation; C is neutron count read with the probe in the field and Cs is a standard count reading from the access tube installed in pure water. The evapotranspiration was calculated from water balance equation used by Payne (1997) as follows:

$$\Delta S = R - (ET + D) \quad [7.4]$$

where ΔS is the change in soil water storage in the root zone, R is rainfall, ET is evapotranspiration, and D is the root zone drainage. The drainage was determined using the method developed by Klaij and Vachaud (1992) as described in Chapter 3. Water use efficiency was calculated using the formula giving by Wang *et al.* (2010) as follow:

$$WUE\ (kg\ m\ m^{-1}) = \frac{Y}{ET} \quad [7.5]$$

where Y is the millet grain yield in kg and ET is the evapotranspiration in mm.

7.2.3.3. Soil and plant materials analysis

Soil samples were taken at the onset of the experiment from 0 to 20 cm in each plot. Each sample was analysed for pH (H_2O) and pH (KCl) using pH meter (with a 1:2.5 soil: water ratio), organic carbon using Walkley and Black's method described by van Reeuwijk (1993); the total nitrogen (N) was determined using Kjeldahl method (Houba *et al.*, 1995). Available phosphorus was measured using Bray-1 method as described by van Reeuwijk (1993). The quantitative determination of total N was done with an auto-analyser using the colorimetric method based on the Bertholet reaction (Houba et al., 1995). Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were extracted by the ammonium acetate (NH_4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). The ions H^+ and Al^{3+} released on exchange by an unbuffered KCl solution was determined using the method described by van Reeuwijk (1993).

The particle size distribution was determined using Robinson method as described by ICRISAT Soil and plant laboratory (2013). *Acacia tumida* prunings and manure sundried samples were analyzed for initial nutrients (N, P and K), lignin, and pholyphenol concentrations. Total nitrogen was analyzed by Kjeldahl methods using a mixture of salicylic acid, H_2SO_4 and selenium for the digestion. The quantitative determination of total N was done with an auto-analyser using the colorimetric method based on the

Bertholet reaction (Houba et al. 1995). The same digest was used to determined total P and K. Total P was quantified with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid and total K was determined with flame emission spectrophotometry (Houba *et al.*, 1995). Lignin was determined using Acid Detergent Fiber (ADF) method described by Van Soest (1963).

Polyphenols content was determined using the Folin-Denis method (Anderson and Ingram, 1993). The details of laboratory protocols used for soil and plant material samples were described in Chapter 3.

7.2.3.4. Statistical analysis

Prior to the analysis, data were carefully checked for normal distribution. Square root transformation was applied to root length density data only to improve normal distribution of the residuals. The analysis of variance was therefore performed with GENSTAT v.9 (Lawes Agricultural Trust, 2007) using a General Treatment Structure (in Randomized Blocks). The model of ANOVA used, included fertilizer micro-dosing option, organic mulch, year and their interactions. Time series data was analyzed based on repeated measures using the AREPMEASURES procedure of GENSTAT v.9. Differences among treatments were considered at error probabilities of ≤ 0.05. Means were compared using least significant difference (LSD) at 5% probability level.

7.3. Results

7.3.1. Soil properties of the experimental field

The results of the initial physical and chemical characteristics of the experimental field are presented in Table 7.2. The texture of the soil was sandy, with only 3.2% clay content. Soil pH (H_2O) and pH (KCl) were 5.4 and 4.4, respectively. The organic carbon level was low (2.2 g kg^{-1}). The nitrogen content of the soil was low (195 mg kg^{-1}). The available P contents and exchangeable bases were very low with 2.8 mg kg^{1} and 1.9 $cmol_c$ kg^{-1}, respectively. The characteristics of this soil are typical of the soils in Niger characterized by sandy texture and low level of nutrients and organic matter.

Table: 7.2. Initial soil properties of the experimental site

Parameters	0-20 cm
Soil texture (%) Sand	94.6 ± 0.1
Silt	2.2 ± 0.1
Clay	3.2 ± 0.2
Soil chemical properties pH-H_2O (1:2.5)	5.4 ± 0.0
pH-KCl (1:2.5)	4.4 ± 0.1
Organic C (g kg^{-1})	2.2 ± 0.0
Total-N (mg kg^{-1})	195 ± 10
P-Bray 1 (mg kg^{-1})	2.8 ± 0.1
Ca^{2+} ($cmol_c$ kg^{-1})	1.31± 0.1
Mg^{2+} ($cmol_c$ kg^{-1})	0.23 ± 0.0
K^+ ($cmol_c$ kg^{-1})	0.16 ± 0.0
Na^+ ($cmol_c$ kg^{-1})	0.19 ± 0.0
H^+ ($cmol_c$ kg^{-1})	0.1 ± 0.0
Al^{3+} ($cmol_c$ kg^{-1})	0.13 ± 0.0

± Standard error

7.3.2. Rainfall distribution during the cropping period

The rainfall distribution during the cropping periods of 2013 and 2014 is shown in Figure 7.1. The total rainfall recorded in 2013 was 481 mm, which is less than the long-term rainfall average at the site of 551 mm yr^{-1}. Most of the rains occurred during

August (from 40 to 60 DAS) which accounted for 75% of the total rainfall recorded during the cropping period in 2013. There was a dry spell of 27 days in September-October in 2013, which coincided with the flowering and grain filling stages. In 2014, rainfall was evenly distributed with 689 mm recorded throughout the growing season (Fig. 7.1).

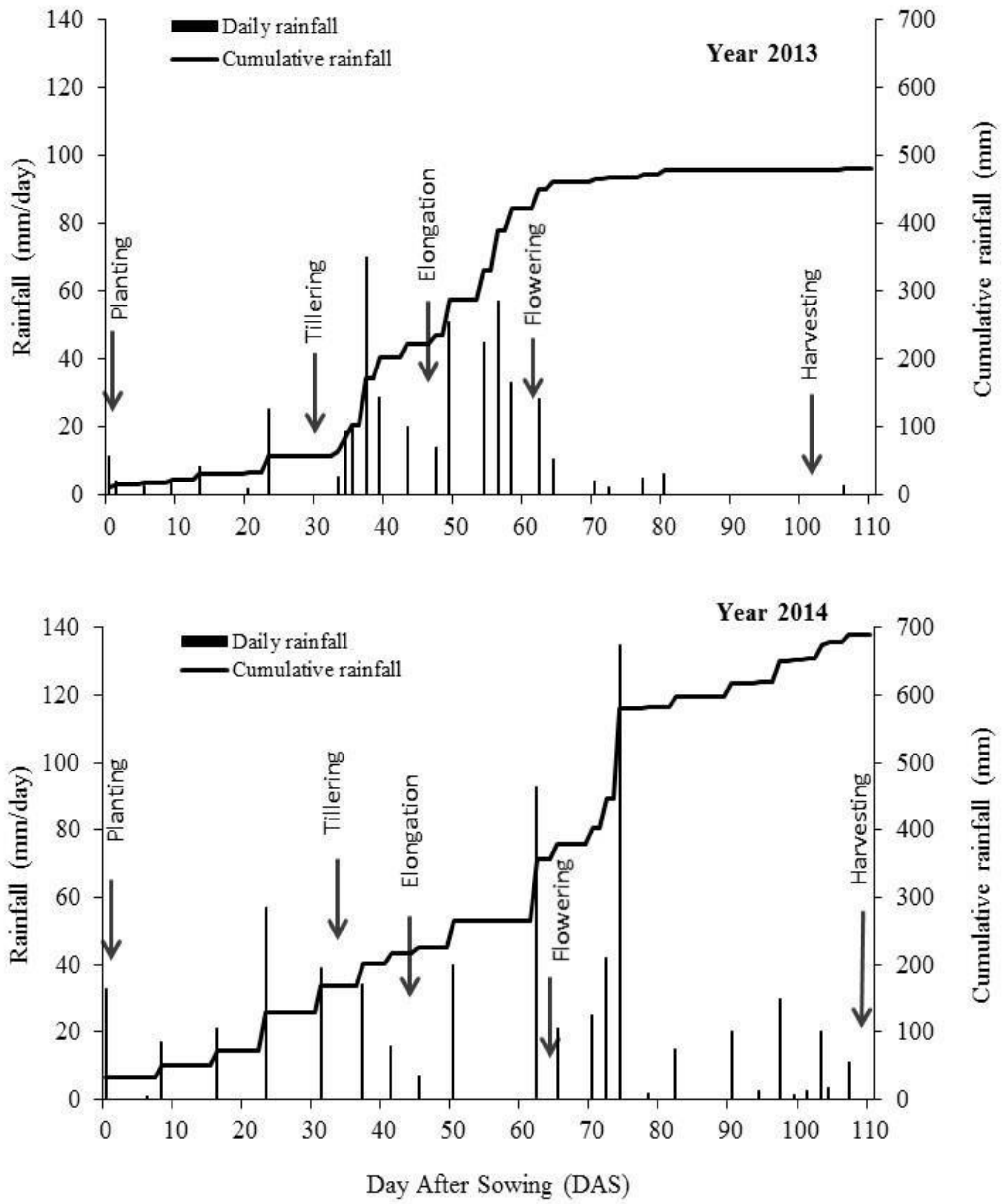

Figure: 7.1. Rainfall distribution in 2013 (upper panel) and 2014 (lower panel)

7.3.3. Root length density

The root length density were highest within the topsoil (0 - 10 cm) and reduced drastically below 10 cm depth (Figure. 2). There were significant differences in root length density among mulching materials ($P < 0.001$). In both years (Figure 7.2a and 7.2b), the RLD in the topsoil (0 - 10 cm) was significantly higher in *Acaica tumida* plots. Below 10 cm depth, the root length density was greater in the plots that received manure treatment particularly in 2014 (Figure 7.2b). The lowest RLD was produced in both years under un-mulched plots.

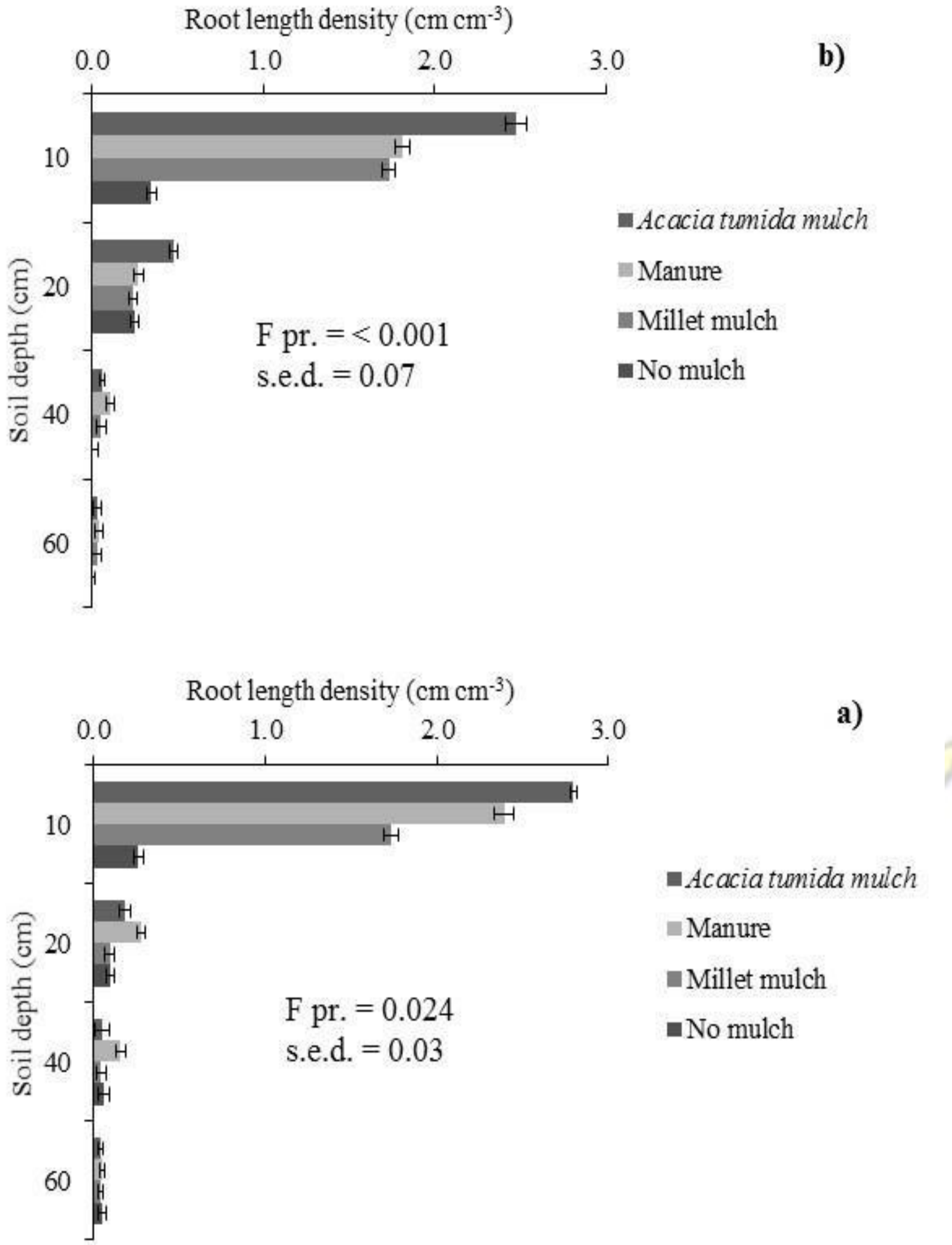

Figure: 7.2. Root length density of millet in a) 2013 and b) 2014

7.3.4. Leaf area index

Leaf area index (LAI) increased significantly with millet growing stages (Figure 7.3). LAI values were significantly higher ($P < 0.001$) in the plots receiving mulches than under the un-mulched plots. However, differences in LAI among plots that received mulching treatments were not significant. Combined application of fertilizer microdosing and organic mulches did not significantly affect LAI (data not presented). In 2013 (Figure 7.3a), the highest LAI (1.6 $m^2 m^{-2}$) was observed in *Acacia tumida* mulching plots at the flowering stage followed by millet straw mulch (1.4 $m^2 m^{-2}$). In 2014 (Figure 7.3b), the highest LAI (1.8 $m^2 m^{-2}$) was recorded in manure plots followed by *Acacia tumida* mulched (1.7 $m^2 m^{-2}$).

7.3.5. Grain and straw yields

Mean millet grain and straw yields as affected by fertilizer micro-dosing and mulching are presented in Table 7.3. Fertilizer micro-dosing increased yields significantly ($P < 0.001$) regardless of the type of organic mulch applied. Application of 2 g DAP $hill^{-1}$ and 6 g NPK $hill^{-1}$ increased grain yield on average by 39% and 16%, respectively compared with the unfertilized control (Table 7.5). The addition of organic mulch to fertilizer micro-dosing treatments caused a marked improvement in millet grain yield over fertilizer micro-dosing treatments alone. Mulching increased grain yield by 38% and 35%, respectively, with 2 g DAP $hill^{-1}$and 6 g NPK $hill^{-1}$ over the un-mulching micro-dosing treatment. The millet grain yields were significantly different among the mulching materials. The average increase in millet grain yield was recorded to be 43, 38% and 26%, respectively for manure, *A. tumida* and millet mulch over the unmulched control (Table 7.5). The addition of organic mulch to fertilizer micro-dosing led to an increase in straw yield of 15 to 27%, depending on the type of mulching materials; straw yields decreased in the following order: *A. tumida* > manure > millet straw (Table 7.5).

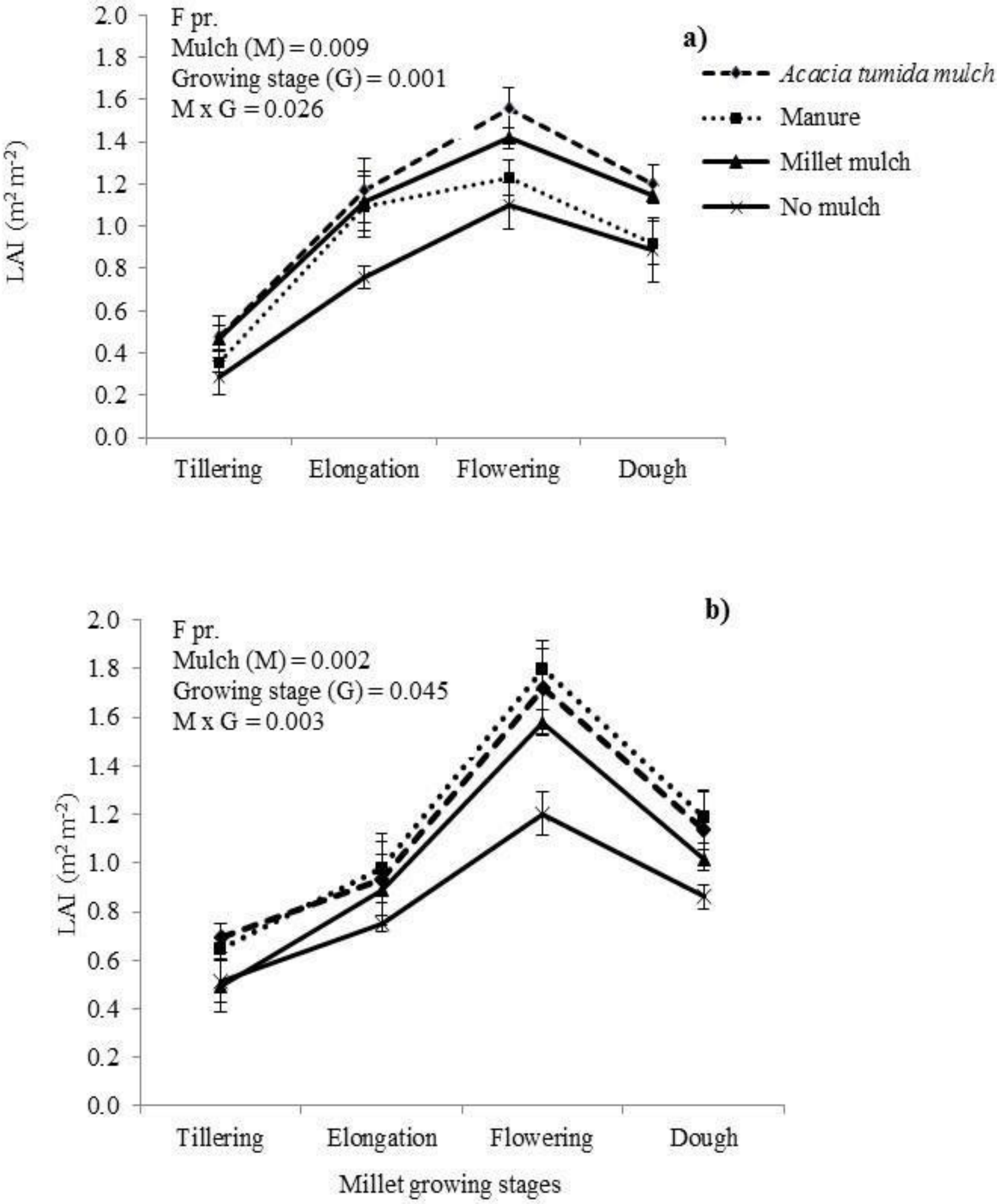

Figure: 7.3. Leaf area index (LAI) in a) 2013 and b) 2014 under mulches

7.3.6. Evapotranspiration, WUE and Soil volumetric water content

Fertilizer micro-dosing and organic mulches did not change millet evapotranspiration (ET) significantly (Table 7.4). However, there was a significant variation in ET among the cropping seasons. The evapotranspiration was higher in 2014 (mean 375 ± 12 mm) than in 2013 (mean 268 ± 4 mm).

Combined application of fertilizer micro-dosing with organic mulch increased water use efficiency (WUE) on average by 31% compared with lone application of fertilizer micro-dosing. Mulches *of A. tumida*, manure and millet straw increased WUE by on average 55%, 49% and 25%, respectively (Table 7.5), while WUE increased by on average 38% with 2g DAP hill^{-1} and by 9% with 6g NPK hill^{-1}.

Soil volumetric water content (VWC) in the different soil layers responded to mulching treatments (Figure 7.4). Throughout the cropping periods, the VWC was significantly higher within 0-15 cm under the plots that received *Acacia tumida* mulch followed by the plots with millet straw mulch (Figure 7.4a and Figure 7.4b). The same trend was observed within 15-30 cm depth (Figure 7.4c and Figure 7. 4d). There was however, no significant difference in VWC between the plots that received manure application and un-mulching plots.

Control	No mulch	402 ± 25	695 ± 147	861 ± 100	
	Manure	507 ± 33	1386 ± 159	1556 ± 309	2694 ± 149
	Millet mulch	570 ± 72	1107 ± 213	1500 ± 210	1944 ± 227
	A. tumida mulch	597 ± 65	1117 ± 70	1806 ± 338	2167 ±173
2 g DAP hill^{-1}	No mulch	780 ± 24	1011 ± 92	1986 ± 141	2194 ± 290
	Manure	742 ± 33	1661 ± 147	1611 ± 169	2917 ± 146
	Millet mulch	843 ± 124	1590 ± 437	2083 ± 250	2639 ± 226
	A. tumida mulch	980 ±121	1611 ± 65	2278 ± 150	2722 ± 200
6 g NPK hill^{-1}	No mulch	611 ± 48	901 ± 49	1667 ± 106	2028 ± 227
	Manure	638 ± 48	1647 ± 185	1639 ± 126	2778 ± 194
	Millet mulch	759 ± 96	1032 ± 145	1750 ± 148	2167 ± 145
	A. tumida mulch	910 ± 83	1126 ± 149	2083 ± 189	2222 ± 168
F pr.					
Mineral fertilizer (F)		< 0.001		< 0.001	
Mulch (M)		0.001		0.004	
Year (Y)		< 0.001		< 0.001	
F x M		NS		NS	
F x Y		NS		NS	
M x Y		0.006		0.01	
F x M x Y		NS		NS	

CV (%)		26		29.8	
		Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})	
Fertilizer micro-dosing	Mulching	2013	2014	2013	2014
					1750 ± 121

Table: 7.3. Grain and straw yields in 2013 and 2014 growing seasons

± Standard error, NS; not significant

Table: 7.4. Evapotranspiration (ET) and water use efficiency (WUE)

		ET (mm)		WUE (kg mm^{-1})	
Fertilizer micro-dosing	Mulch	2013	2014	2013	2014
Control	No mulch	278 ± 24	362 ± 16	1.5 ± 0.1	1.8 ± 0.3
	Manure	281 ± 17	366 ± 28	1.8 ± 0.2	3.9 ± 0.6
	Millet mulch	247 ± 5	321 ± 19	2.4 ± 0.1	3.5 ± 0.4
	A. tumida mulch	255 ± 10	311 ± 27	2.3 ± 0.2	3.6 ± 0.1
2 g DAP hill^{-1}	No mulch	266 ± 7	349 ± 47	2.9 ± 0.1	3.1 ± 0.1
	Manure	272 ± 8	379 ± 23	2.7 ± 0.1	4.5 ± 0.5
	Millet mulch	292 ± 22	427 ± 38	2.9 ± 0.2	3.6 ± 0.6
	A. tumida mulch	259 ± 10	338 ±13	3.8 ± 0.4	4.8 ± 0.1

6 g NPK hill^{-1}	No mulch	263 ± 13	391 ± 33	2.7 ± 0.2	2.3 ± 0.6
	Manure	276 ± 16	405 ± 30	2.3 ± 0.1	4.1 ± 0.4
	Millet mulch	263 ± 11	440 ± 36	2.3 ± 0.1	2.4 ± 0.3
	A. tumida mulch	266 ± 4	405 ± 43	3.4 ± 0.2	2.8 ± 0.1
F pr.					
Mineral fertilizer (F)		NS		< 0.001	
Mulch (M)		NS		< 0.001	
Year (Y)		< 0.001		< 0.001	
F x M		NS		NS	
F x Y		NS		NS	
M x Y		NS		0.002	
F x M x Y		NS		NS	
CV (%)		20.3		26.4	

± Standard error, NS; not significant

Table: 7. 5. Increased in grain yield, straw yield and WUE over the control

	Grain yield (kg ha^{-1})	Increased in grain yield as compared to control (%)	Straw yield (kg ha^{-1})	Increased in straw yield as compared to control (%)	WUE in Grain (kg mm^{-1})	Increased in WUE as compared to control (%)

Fertilizer micro-dosing							
	Control	823^{b}		1785^{b}		2.7^{b}	
	2 g DAP $hill^{-1}$	1152^{a}	39	2304^{a}	29	3.7^{a}	38
	6 g NPK $hill^{-1}$	953^{b}	16	2042^{a}	14	2.9^{b}	9
Mulching material							
	No mulch	767b		1748^{b}		2.3^{b}	
	Millet straw	984^{a}	26	$2014a^{b}$	15	2.9^{b}	25
	Manure	1097^{a}	43	2199^{ab}	26	3.5^{a}	49
	A. tumida mulch	1057^{a}	38	2213^{a}	27	3.6^{a}	55
Lsd (0.05) for: Micro-dosing		147		235		0.48	
Mulching material		171		271		0.55	

Means within column followed with the same letters are not significantly different at P < 0.05

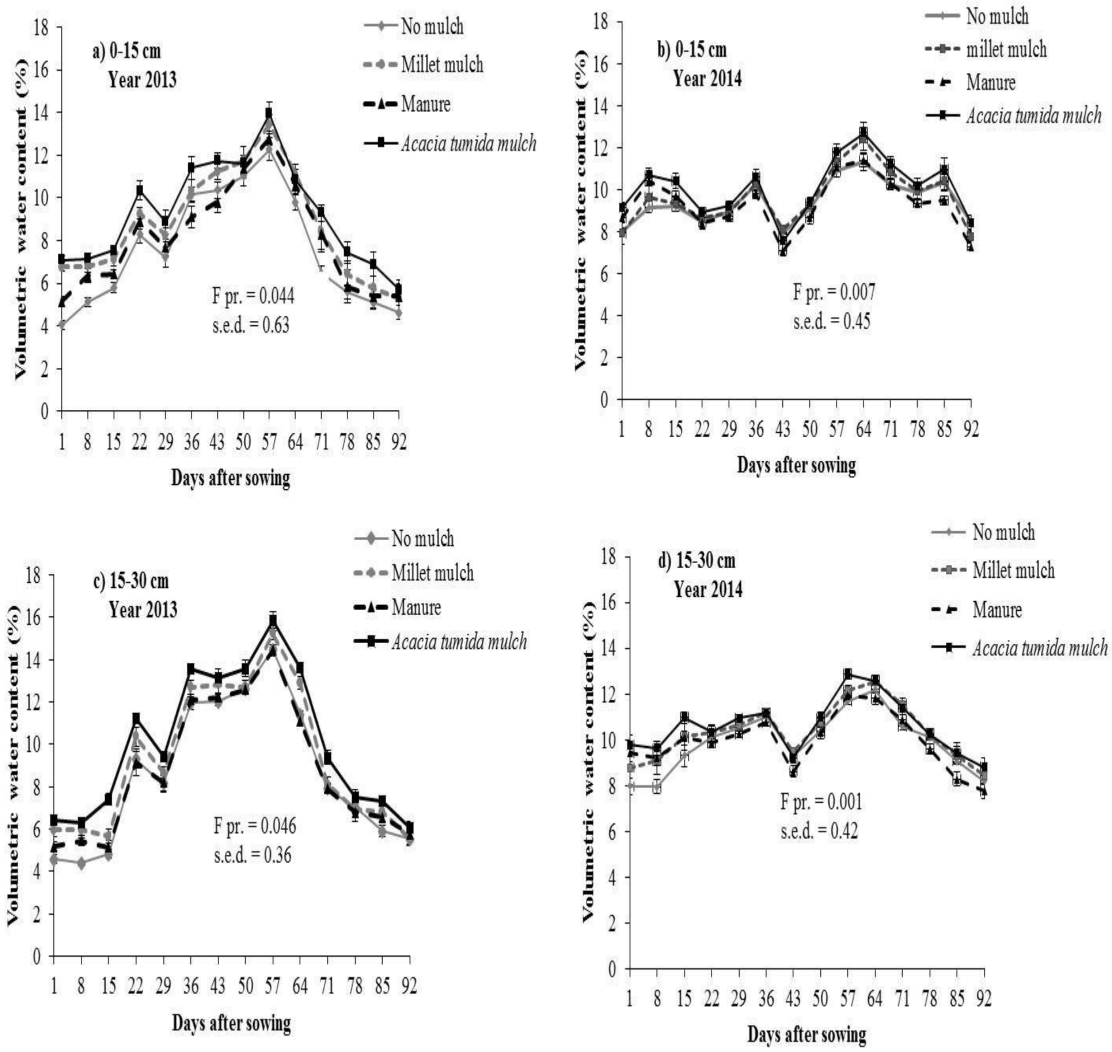

Figure: 7.4. Volumetric water content in 2013 and 2014. Vertical line indicate standard error.

7.4. Discussion

The results showed that fertilizer micro-dosing significantly increased millet yield compared with no application of fertilizer (Table 7.3). The current results support the earlier reports on micro-dosing regarding the effectiveness of the technology in improving crop yield under low-input millet based system (Bagayoko *et al.*, 2011; Bielders and Gérard, 2014; Ibrahim *et al.*, 2014).

There was a significant seasonal difference in millet yields recorded in the current study; yields were higher in 2014 than in 2013. The seasonal yield variability could be attributed to the larger amount of rainfall and better rainfall distribution observed throughout the growing period in 2014 (Figure 7.1) which ultimately favoured better plant growth and biomass production. The differences in yields recorded in 2013 and 2014 may also be attributed to the residual effect of the organic mulches applied. Bationo *et al.* (1993) had earlier reported of similar significant millet yield responses in the second year of crop residue application. The probable explanation for the residual effect of mulching in the following year could be the enhanced supply of nutrients and water through nutrient recycling, wind-blown dust trapping, and reduced evaporation (Movahedi Naeni and Cook, 2000; Ram *et al.*, 2003; Schlecht *et al.*, 2006). This residual effect may also explain the significant interaction between mulch and year on grain and straw yields (Table 7.3).

The results also showed that millet yields may be increased further by organic mulches (Table 7.3). Increases in yields under mulch have been attributed to the higher water retention capacity of soil and efficient use of available rainfall which encourage root proliferation and thereby promote better crop growth in the early season under arid and semiarid environment (Chakraborty *et al.*, 2008). This was demonstrated in the highest LAI and root length density recorded in mulched plots at the early stage of millet development (Figure 7.3). This study produced results which corroborate the findings of Vial *et al.* (2015) who showed an early-season effect of mulch on crop growth. Furthermore, the greater root length density observed in the topsoil under mulched plots (Figure 7.2) could improve P mobility and more importantly water availability thereby improving the grain yield (Li *et al.*, 1999). A positive effect of mulching in combination with mineral fertilizer on millet yield in the Sahel has also been reported by Bationo *et al.* (1993) and Yamoah *et al.* (2002). However, the response of millet yields to mulch depends on mulching material applied. In 2013, *A.*

tumida mulch was the best in producing high millet grain and straw yields followed by the millet mulch. Conversely, in 2014, the highest yields (Table 7.3) were documented in manure plots, followed by *A. tumida* and millet mulches, respectively. The high yield recorded with *A. tumida* in 2013 season could be explained by the improvement of soil moisture content as a result of the reduction in soil evaporation rate. This was less the case with manure, because soil volumetric water content was lower with manure than with *A. tumida* and millet straw mulches (Figure 7.4). The present observation is consistent with that of Cook *et al.* (2006) who found significant evaporative loss under farmyard manure compost compared to wheat and soybean straw. Yet, the higher yields in manure plots in 2014 suggest that in a relatively wet season, the mulching effect could be enhanced by improved nutrient supply from the mulch (Ram *et al.*, 2003). In addition, the relative high lignin content of *A. tumida* pruning (Table 7.1), could hamper the nutrient release from this mulching material. The slow decomposition rate of *A. tumida* mulch could be an advantage because it stays in the soil for a longer period of time, and therefore restricts soil water from evaporation loss and also protect soil against wind erosion losses. This result indicates that application of *Acacia tumida* prunings as mulch could improve crop water availability and allow better use of limited rainwater particularly in high drought risk areas such as the Sahel.

The evapotranspiration (ET) was not affected by any treatment in the current study. However, there was a significant seasonal variation in evapotranspiration (Table 7.4). The variation in evapotranspiration between the cropping years can be attributed to the difference in rainfall recorded between the two experimental years (Figure 7.1). Application of mulches significantly increased WUE compared with the no-mulch treatment (Table 7.4). About 50% increase in WUE was noted in *A. tumida* plots followed by manure (46%) and millet mulch (26%) in comparison with the no-mulch plots (Table 7.5). This observation is in conformity with reports from previous studies which demonstrated the effectiveness of organic mulch in reducing soil evaporative rate and increasing WUE (Huang *et al.*, 2005; Chakraborty *et al.*, 2008). However, the current study further shows that the mulching effect on improved water use efficiency depends on the type of mulching material applied. The application of *A. tumida* mulch more significantly increased WUE compared to the millet mulch (Table 7.5). It appears that the potential of *A. tumida* in increasing WUE is attributable to its capacity to conserve soil water in upper soil layers (Figure 7.4). This is in accordance with the results from previous studies that demonstrated that any practice that leads to an increase in soil water availability in the upper portion of the root may have a positive impact on WUE and improve nutrient uptake (Payne, 1997; Hatfield *et al.*, 2001).

7.5. Conclusion

Organic mulches had an evident effect on millet yield and WUE. Combined application of fertilizer micro-dosing and organic mulches is an effective fertilization strategy for improved millet production in the Sahelian semi-arid environment. *Acacia tumida* pruning could serve as an appropriate mulching alternative for further increasing crop yield and water use efficiency in the biomass-scarce and drought prone environment such as the Sahel. However, the economic and social implications and the long-term agronomic effects of this agro-forestry tree in Sahelian millet based system have to be explored.

Chapter Eight

General discussion

Chapter Eight

8. General discussion

Soil fertility decline is generally a major constraint to crop production in the Sahel (Smaling *et al.*, 1993). Inorganic and organic fertilizers are often unavailable in adequate quantities for applications in smallholder cereal cropping systems to increase crop productivity (Bationo *et al.*, 2003). To increase crop yields and encourage farmers to apply inorganic fertilizer, micro-dosing technology was developed and gave promising results in improving crop yields, fertilizer use efficiency and economic return (Tabo *et al.*, 2007; Bielders and Gérard, 2014). The objectives of this research were to (1) explore the mechanisms governing the growth enhancing phenomena of the fertilizer micro-dosing technology, (2) assess the potential effects of integrated use of organic amendment and fertilizer micro-dosing in improving millet yield and water use efficiency and (3) evaluate the extent of nutrient gains and losses under fertilizer micro-dosing by estimating nutrient balances. The main findings of the current study are discussed in the following paragraphs.

8.1. Determinants of fertilizer micro-dosing induced millet yield increase Rapid root growth and desired root architecture development play an important role in nutrients and water acquisition by plants in low soil fertility and dry environments. The current study demonstrates a marked increase in millet root length density at early crop growth with fertilizer micro-dosing treatments. The increase in root growth in the early crop growth stage stimulates uptake of soil nutrients such as phosphorus because of the high capacity of young roots in improving nutrients uptake (Smit *et al.*, 2013;

Ma *et al.,* 2014). Increase in leave chlorophyll content at tillering stage led to an increase production of photosyntates for enhanced leaf area development and biomass production. This enhanced early growth of crop is therefore viewed as a plausible explanation for the positive effect of fertilizer micro-dosing in increasing millet yields. However, the millet roots under fertilizer micro-dosing treatments did not penetrate in deeper soil layers to scavenge for nutrients and water as compared with the scenario under broadcasting of mineral fertilizer. Millet roots were concentrated in the topsoil layers where the nutrients are accumulated. Nevertheless, the findings in this study are in disparity with the previous research by Aune and Bationo (2008) who argued that the reason of fertilizer micro-dosing-induced crop yield increases was due to the positive effect of this technology in stimulating root growth in the deeper soil layers which, therefore, enhance soil nutrient and water uptake. The concentration of millet roots in the topsoil with fertilizer micro-dosing was in line with crop response to the localised application of nutrients leading to roots proliferation in the patches with high nutrient concentration (Hodge, 2009). The current research finding implies that in a sandy soil characterized by a shallow soil depth and where most of the nutrients are concentrated in the topsoil, the proliferation of the roots within this soil profile can be of immense benefit to the crop. Yet, in the areas where dry spells are common occurrences, the crop has to cope with the recurrent dry spells throughout the cropping period by the extraction of the water accumulated in the deeper soil layer. These results indicate that probably the quantity of nutrients applied through fertilizer micro-dosing was not sufficient enough to induce root growth in deeper soil layers with high water reserves and thereby enhance water use. The development of deep rooting system in the dry conditions is needed for improving further nutrients and water use by the plant. It has been established that the application of good quality organic amendment promotes rapid proliferation of roots in deeper soil layers (Fatondji, 2002). It, therefore, becomes necessary to supplement fertilizer micro-dosing with the organic amendment in order to promote rapid and deep root growth.

8.2. Combined application of fertilizer micro-dosing and manure

The findings reported in Chapter 5 showed a significant increase in millet yield and total dry matter production when manure was added to the fertilizer micro-dosing treatments. Increase in grain and total biomass yields due to the combined application of fertilizer micro-dosing and manure was accompanied by an increase in the water use efficiency (WUE). These results are in close agreement with the results of Liu *et al.* (2013) who showed that applications of fertilizer and manure not only accelerated soil fertility improvement but also maintained soil water balance, and significantly improved crop yields in the short term. The positive effect of manure on millet yields under fertilizer micro-dosing is attributable not only to the supply of additional nutrients such as Ca and Mg (Bayu *et al.*, 2005; Zingore *et al.*, 2008) which are lacking in sufficient quantities in this experimental sandy soil. This positive effect can also be attributed to the low level of organic matter content which limits soil water and nutrient retention in this sandy soil. The method of manure application markedly affects millet response to fertilizer micro-dosing. The hill placement of manure performed better in improving millet grain yield and dry matter than broadcasting. It seems possible that the positive effect of hill placement of manure could have resulted from a better exploitation of the limited amount of nutrients by the root due to early root proliferation. The concentration of manure in the vicinity of crop rooting system, such as was the case in hill application of manure, led to the creation of a “micro-climate” around the plant root system which resulted in the rapid and early root growth. Increased root proliferation increases the volume of soil colonized and thereby increasing the potential of water and nutrient use. Generally, plants provided with adequate nutrients supply extend root into the deeper soil layers for extracting the necessary resources for its growth (Payne *et al.*, 1995). However, the roots growth pattern in manure hill placement tended to be more profuse in the topsoil where nutrients are mostly concentrated. This finding confirms our results in Chapter 4 which showed an accretion of millet roots in the topsoil under fertilizer micro-dosing. It is somewhat surprising that when manure was broadcast, roots tended to penetrate into deeper soil layers probably to scavenge for water particularly in 2013 when the crop experienced a long dry spell during the reproductive phase. Though, the manure broadcast was incorporated superficially into the soil, it seems possible that the incorporation of manure had improved soil conditions which facilitated root penetration in deeper soil layers thereby improving soil water and nutrients use. Increased roots growth through combined application of manure and fertilizer microdosing has a great implication on soil nutrient reserves.

8.3. Assessing nutrient balances under fertilizer micro-dosing

The main question that this study attempted to answer was whether fertilizer microdosing could sustain crop production. The most obvious finding that emerged from this study was that the increase in yields with fertilizer micro-dosing was accompanied by an increase in soil nutrient uptake which resulted in negative nutrient balances. The present study provides additional evidence that continuous cropping with the current fertilizer micro-dosing recommendations without adequate restorative practices of soil fertility could not sustain crop productivity in low-input cropping systems where the soils are characterized by low nutrient stocks. Yet, the extent with which nutrients are exported depends on the yields of crops and the amounts of nutrients removed. The combination of fertilizer micro-dosing with manure seems to give better yields but the nutrients exported appeared to be excessive as a result of higher biomass production.

The results reported in this study indicated that crop residues removal magnified the nutrients depletion which accounted for on average 66% N, 55% P and 89% K. It appears that soil fertility management to sustain crop production under fertilizer microdosing technology might involve the maintenance of crop residues in the fields. The retention of crop residues in the fields has an important implication not only in increasing soil nutrients availability (Geiger *et al.*, 1992) but also in protecting soil against wind erosion which is one of the major sources of soil nutrient losses in the Sahel (Bielders *et al.*, 2001). However, the issue of crop residues management in the smallholder Sahelian farming systems is a challenge due to multiple competing uses (Valbuena *et al.*, 2014). The exploration of other alternative sources for crop residue becomes, therefore, vital for sustaining crop production in low-input cropping systems.

8.4. Potential of *A. tumida* mulch and fertilizer micro-dosing in increasing yield and water use efficiency

The multiple uses of crop residues and limited availability of such mulching materials in adequate quantity increases the need to search for other sources of organic amendments to improve crop productivity and maintain soil fertility in low-input Sahelian cropping systems. The findings reported in this study (Chapter 7) showed that adding organic mulch to fertilizer micro-dosing increased grain yield by 37%. The grain yield increases relative to the un-mulched control were 51% for manure, 46% for *A. tumida* mulch and 36% for millet mulch while the addition of *A. tumida* pruning, manure and millet mulches increased WUE on average 55%, 49% and 25%, respectively. The present findings are consistent with other studies which reported an increase in yields and water use efficiency under mulch as a result of higher water retention capacity from available rainfall which encouraged root proliferation. This favoured better crop growth in the early season under arid and semiarid environment as previously explained by Chakraborty *et al.* (2008), Tilander and Bonzi (1997) and Wezel and Boecker (1999). The use of agro-forestry mulches is not common in the Sahelian zone of Niger owing to the lack of biodiversity and the dominance of the cropping systems by a narrow range of annual crop species (Rinaudo and Cunningham, 2008). This study has demonstrated that *Acacia tumida* pruning could serve as a suitable mulching alternative for further increasing crop yield and water use efficiency in the biomass-scarce dry areas of Sahel. Though, the current study has only examined the mulching effects of *A. tumida* on yields and water conservation, the incorporation of this agro-forestry trees in the low-input cropping systems can also supply various other services, especially fire wood, and improvement of soil fertility through fixation of atmospheric nitrogen (Rinaudo *et al.*, 2002).

Chapter Nine

General conclusions and recommendations

Chapter Nine

9. General conclusions and recommendations

9.1. General conclusions

Based on the objectives and the results obtained in the current study, the following conclusions can be drawn:

1. Fertilizer micro-dosing is an effective fertilization strategy for improving millet productivity in low-input Sahelian cropping systems. The positive effect of fertilizer micro-dosing in increasing millet yield results from the better exploitation of soil nutrients due to early proliferation of lateral roots within the topsoil. These results therefore provide an abundant room for further progress in determining the contribution of fertilizer micro-dosing, for example in increasing mycorrhizal infection for enhancing plant growth and nutrient uptake in low-input millet-based cropping systems.
2. Combined application of fertilizer micro-dosing with manure hill-placement improved millet yield and water use efficiency further. These results highlighted the importance of increasing soil organic matter content of extremely sandy soils for enhancing water and nutrient use efficiency. The results obtained indicate that the use of 2000 kg ha^{-1} of manure and 20 kg DAP ha^{-1} hill-placement appeared to be the most appropriate combination for improving millet yield, and water use efficiencies in the Sahelian millet-based system.
3. The nutrients applied through fertilizer micro-dosing and manure are not sufficient to balance the nutrients uptake by the crop which led to negative nutrient balances. The negative nutrients balances were exacerbated by the

export of straw yields from the field which accounted for on average 66% N, 55% P and 89% K exportation. It, thus, appears that fertilizer micro-dosing increases the risk of soil nutrients depletion because the high productivity relies mainly on the native soil nutrients stock. This result has important implications for developing an agro-ecological approach to address sustainable food production in the Sahelian smallholder cropping systems.

4. Combined application of fertilizer micro-dosing and organic mulches is an effective fertilization strategy for improved millet production in semi-arid environment of Niger. *Acacia tumida* pruning could serve as an appropriate mulching material for increasing millet productivity and water use efficiency in the biomass-scarce dry areas of Sahel.

9.2. Limitations of the research and recommendations

The limitation of the current study was related to the use of the transfer functions and secondary data to calculate full nutrient balances which may have led to the over or under-estimation of nutrient losses due to leaching and erosion which are the major sources of soil nutrients depletion particularly in Sahelian low-input cropping systems. Further experimental work will be needed for quantification of these flows in order to provide an accurate indication of potential nutrient mining effect of fertilizer microdosing.

In order to sustain crop production under fertilizer micro-dosing the following recommendations are made:

1. Farmers should be encouraged to (a) retain crop residues in the fields for recycling nutrients and protecting soil against wind erosion which is one of the main sources of soil depletion in the Sahel, (b) use other sources of mulching

material such as *A. tumida* which has been shown to be a suitable alternative to the scarce crop residues.

2. Incorporate legumes such as cowpea into cereal-based cropping systems to increase biological nitrogen fixation (BNF) for improving soil nitrogen content and reducing soil N depletion.

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