SOIL NUTRIENT DYNAMICS UNDER LONG TERM APPLICATION OF MINERAL FERTILIZER MICRO-DOSING TO PEARL MILLET [*Pennisetum glaucum (L)*] ON A SAHELIAN SANDY SOIL OF NIGER REPUBLIC

BY

SANI ISSA, Mahaman Sanoussi
MTech/SPS/2015/6067

THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF TECHNOLOGY (MTech)
IN CLIMATE CHANGE AND ADAPTED LAND USE

MARCH, 2018

DECLARATION

I hereby declare that this thesis, titled: **"Soil Nutrient Dynamics under Long Term Application of Mineral Fertilizer Micro-dosing to Pearl Millet [*Pennisetum glaucum (L)*] on a Sahelian Sandy Soil of Niger Republic"** is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) have been duly acknowledged.

SANI ISSA, Mahaman Sanoussi ------------------------

MTech/SPS/2015/6067 SIGNATURE/DATE

FEDERAL UNIVERSITY OF TECHNOLOGY,

MINNA, NIGERIA.

CERTIFICATION

The thesis titled: "**Soil Nutrient Dynamics under Long Term Application of Mineral Fertilizer Micro-dosing to Pearl Millet [*Pennisetum glaucum (L)*] on a Sahelian Sandy Soil of Niger Republic"** by SANI ISSA, Mahaman Sanoussi (MTech/SPS/2015/6067) meets the regulations governing the award of the degree of Master of Technology of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

Prof. M. I. S. Ezenwa	……………………………
Supervisor	Signature & Date
Prof. A. A. Okhimamhe	……………………………
Director, WASCAL-FUT, Minna	Signature & Date
Prof. M. G. M. Kolo	…………….……………
Dean, Postgraduate School	Signature & Date

DEDICATION

This piece of work is dedicated to the Niger Republic, to my beloved parents, Late Elhadji Sani, Issa and Sahouna, Garba and to my wife (Mrs.) Mariam M. I. Sanoussi.

ACKNOWLEDGEMENTS

First of all, all praises are indeed to Allah for giving the strength to accomplish this Master Research well in a giving period of time. It is with immense gratitude that I would like to express my warm thanks to some people and organisations that have played key roles in the success of this piece of work. This research was indeed fully funded by the German Federal Ministry of Education and Research (BMBF) through the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). I express my special gratitude to these two institutions for their support.

I am most grateful to Prof. Ezenwa M. I. S., my supervisor, for his professional support and guidance without which this work would never be successful. My heartfelt thanks go to my Co-Supervisor Dr. Dougbedji Fatondji for accepting me as a trainee at ICRISAT Sadore in Niger Republic. I am deeply grateful for his availability, his guidance, his encouragement, his advice and valuable inputs to this work despite his busy schedule. He always kept his door open for discussions on this work. My gratitude goes also to Prof. Okhimamhe, A.A; the Director of WASCAL MRP on Climate Change and Adapted Land Use (CC&ALU) at Federal University of Technology, Minna. I acknowledge her continuous support and encouragement, and the provision of long-lasting motivation. My appreciation also goes to WASCAL CC& ALU staff for their understanding, their hospitality and constant assistance in everything. I would like to thank technicians and field assistants of ICRISAT-Sadore particularly to Dr Ali Ibrahim for helping to handle statistical analyses as well as Laouali Issaka and Moustapha for their hospitality, their professional assistance and moral support during my fieldwork at ICRISAT. I am also deeply grateful to my parents for their moral support and their patience specially my beloved mother Sahouna Garba. My exceptional thanks go to my wonderful wife Mme Sanoussi Mariam Maman Inoussa for her great understanding, full support and patience for my absence.

I express my sincere thanks to all my MRP WASCAL CC& ALU staff for their support. Finally, many thanks to all my WASCAL CC& ALU course mates for their support during our stay in Minna. Fafa Cham and Big Koro, the man (me) in charge of washing plates and pots expresses his gratitude for your delicious meals.

ABSTRACT

Low soil fertility and insufficient rainfall are the major constraints limiting pearl millet yields in Niger. Thus, to address these striking constraints, institutions working in Sahel joined forces through a collaborative research programme and developed an effective technique known as fertilizer micro-dosing (application of small doses of fertilizer in the hill of the target grain crop at planting) in order to tackle these issues. Reports from the implantation of the technology have shown up to 120% of yield increase. However, the question is whether the application of this technology would not lead to soil nutrients mining in the long-term. A study was set at ICRISAT which aims at evaluating the sustainability of the technology in the long-term with regard to pearl millet productivity and with emphasis on soil nutrient dynamics. As a long-term experiment, the study started since 2008 and was laid out in a randomized complete block design that involved two pearl millet varieties, three planting densities, and four nutrients management options. For the purpose the present research, a sub-set of the treatments from this long term experiment was used. The nutrient management options considered include the control, 2kg.ha^{-1} of DAP+ 1kg.ha^{-1} of Urea at elongation stem period, 30 kg. ha^{-1} of NPK and 60 kg. ha^{-1} of NPK. Soil survey was carried out in each of the corresponding plots, soil samples were collected both between and on the planting hills. A total of 36 soil samples were collected and analyzed at Soil Lab of ICRISAT-Sahelian Centre Sadore. The results showed significant decline in soil nutrient over years. The change in soil nutrient was markedly different on the planting hills and that from between hill spaces. The change in soil pH-H_2O values on the planting was -7.06% for the control plots and -9.57% for the plots treated with NPK. Hence, this negative change resulted in possible acidification of the experimental site. The total nitrogen content dropped in both the control plots and the plots that received NPK as micro dose. The percentage of change decreased with the application of NPK microdosing on the planting hills with respectively -5.11% and -12.45% in the control plots and the plots receiving NPK. Positive significant change in available P was observed ($P \leq 0.05\%$) in soil between hill with 1.08% in the control plots and 15.97% in the plots amended with NPK. Whereas on the planting hills, the change was higher in plots treated with NPK compared to the control plots with respectively 88.19% and -6.27%. Further, the trend of the change observed in soil organic carbon content on the planting hills was -21.85% and -26.71% in micro-dosing plots and in the control plots respectively. Both stover yield and total biomass showed similar trend in which decreased yield was obvious over the years. In 2009, Average stover yield of 4053 Kg. ha^{-1}, 5867 Kg. ha^{-}1, 6667 Kg. ha^{-1} and 5360 Kg. ha^{-1} was obtained respectively for the control plots, 2g DAP +1g Urea plots, 3g NPK plots and 6g NPK plots. Whereas in 2010, the stover yield decreased by 31%; 18.47%; 13% and 26.12% respectively for the control plots, the plots applied with 20Kg.ha^{-1}of DAP plus 10Kg. ha^{-1} of Urea, 30Kg.ha^{-1} of NPK plots and 60Kg.ha^{-1} of NPK. Grain yield also dropped in 2010 compared to 2009 by 36% for the control plots, 62.6% for the plots applied with 20Kg. ha^{-1} DAP plus 10 Kg. ha^{-1} Urea and 43.65% for the plots applied with 60Kg. ha^{-1} of NPK. These findings showed that in the Sahel low-input based millet cropping systems, for the micro-dosing fertilizer technology to be sustainable in the long term, the improvement and maintenance of soil fertility should be considered as the cornerstone.

TABLE OF CONTENTS

Content **Page**

List of figures

Figure **Page**

List of plates

List of tables

List of abbreviations

DAP: Diamonium Phosphate

FAO: Food and Agriculture Organization

GHG: Green House Gases

IFA: International Fertilizer Association

IPCC: Intergovernmental Panel on Climate Change

ICRISAT: International Crop Research Institute for the Semi-Arid Tropics

NPK: Nitrogen Phosphorus and Potassium

RCBD: Randomized Complete Block Design

SLM: Sustainable Land Management

SSA: Sub-Saharan Africa

SOC: Soil Organic Carbon

USDA: United States Department of Agriculture

WASCAL: West African Science Service Center on Climate Change and Adapted Land Use

CC&ALU: Climate Change and Adapted Land Use

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Africa's economic development is dependent upon agriculture and agro-industry sectors that are mostly affected by land degradation (Henao and Baanate, 2006). Sub Saharan African(SSA) regions are facing tremendous challenges with regards to food security (Wolf *et al*., 2016). Further, the rapid population growth has led to the use of even the marginal land and hence degradation of arable lands. Many studies illustrate that soil nutrients that plant takes are well above the inherent or applied nutrient in Sahel areas as Bagayoko *et al.* (2011) indicated. Further, Zougmoré et *al.*, (2014) noted that in the semi-arid zones of Western Africa, main constraints that have negative impacts on the development of agriculture are soil acidification and nutrient depletion.

In African soils, Henao and Baanate, (2006) reported that nutrient losses resulting from erosion account for about 40 kg NPK/ha/year and if it continues without cessation, reductions in yields by 2020 could be 30%. In the same way, in Sahel, crop yield is low because of soil nutrient deficiency and a lower organic matter content.

Therefore, increasing agricultural productivity should necessarily pass through soil fertility improvement (Bationo et *al.*, 2006). Hence, to increase and sustain crop productivity under such conditions efficient management of soil nutrients and organic matter is necessary. Considering the limited availability and the high price of external nutrients sources such as mineral fertilizer or organic manure, their judicious application is required to improve productivity and effectiveness. Therefore, micro-dosing organic and mineral fertilizer appears to be one of the most beneficial nutrients management strategies. It is a solution for improving crop production in Sadore due to its positive effect on crop yield as well as on dynamics of root length density (Ibrahim *et al*., 2016; Ahmed *et al*, 2016; Ibrahim *et al.*, 2015; Ibrahim *et al.*, 2014; Maimmouna, 2010).

1.2 Statement of the Problem

In many areas of SSA, land degradation is particularly severe and obvious. Bationo *et al.* (2012) indicated that in the dryland of Africa in general and the Sahel in particular, agriculture is practiced in a severe environment, with low soil fertility as a result of mismanagement practices that constitute the main characteristics. Soils have intensively lost their physical properties, become less structured with crusting and also little nutrient content. Further, low soil fertility is among the most limiting factors of crop production as reported by Nakamura *et al*., (2010).

A decline in soil fertility resulting from mono-cropping, degraded soils and other factors, often blamed for the drop in crop yields across Africa, ought to encourage African smallholder farmers to use fertilizers (Busani, 2016).

Furthermore, Socio-economic conditions of small farmers, such as poor asset-base and poor access to markets, are also regarded as major constraints in crop productivity. As a consequence, while some countries are capable enough to use about 80 kg/ha of fertilizer, in the dryland of Africa it is limited to less than 8kg/ha annually (Abuja, 2006).

Further, the usage of mineral fertilizer remains low in Sahelian millet based farming system. Fertilizer intake in 55% of SSA countries including Niger is not up to 5 kg. ha^{-1}(Abuja, 2006; Busani,2016).

Therefore, it is observed a lack of sustainable land management strategies that permit the improvement of crop productivity and fortunately, the micro-dosing fertilizer application is one of the most important and beneficial land management strategies for improving crop productivity in Sadore. However, there exists scanty information with respect to the sustainability of the technology in the long-term even though it gives a high yield increase.

1.3 Justification of the Study

Pearl millet is the staple crop cultivated in Niger Republic and the region is witnessing a great drop with regard to fallow system as a strategy for soil fertility improvement (Tabo *et al*., (2006). Fortunately, the development of the micro-dosing technology by ICRISAT and partners is aimed at helping dryland farmers in this management process. Studies conducted from the implementation of this technology have shown up to 120% yield increase (Tabo *et al*., 2007). However, such a high yield increase could imply consequent nutrient uptake. This may affect negatively agricultural productivity and land resource integrity. Because Sahelian soils are acidic (pH 4 to 5 (H_2O)) and low in nutrients and carbon content (0.2%) the main question remains as whether soil nutrient imbalance would not occur in the long term following the application of the technology (Abuja, 2006). Therefore, additional studies are necessary to make such a successful technology sustainable for pearl millet production.

1.4 Initial Assumptions

For the purpose of the present study, the general hypothesis is that as a result of hill application of the mineral fertilizer micro-dosing, soil nutrient dynamics on the planting hill will be better and different from that of the soil between the planting hills and hence will affect crop yield over the years.

1.5 Research Questions

(i) What is the contribution of hill nutrient dynamics to the sustainability of micro-dosing technology from nutrients management point of view?

(ii) How do between hills nutrients dynamics contribute to the sustainability of the technology from nutrients management point of view as well?

(iii) Does soil nutrient dynamics affect crop yield over the cropping seasons?

1.6 Aim and Objectives of the Study

The study aims to assess the sustainability of mineral fertilizer micro-dosing technology with regard to pearl millet productivity with emphasis on soil nutrients dynamics.

The objectives of the study are to:

(i) Assess nutrients dynamics from long-term mineral fertilizer microdosing application to pearl millet on a Sahelian sandy soil,

(ii) Determine the level of contribution of planting hill and between planting hill focused nutrient dynamics to soil fertility sustainability of fertilizer microdosing application and

(iii)Evaluate the effect of mineral fertilizer micro-dosing on crop yield over the years.

1.7 Scope of the Study

The scope of the study was Sadore village where ICRISAT is located. Our study is limited at ICRISAT station rather than the whole of the said village.

This study is a kind of contribution that allows us to strengthen more the collaboration between the two institutions (WASCAL and ICRISAT). One of the most important objectives of ICRISAT-Sahelian Centre is to develop cropping systems that contribute to increase and stabilise crop yield on a sustainable land use basis. Subsequently, WASCAL research programme focuses also on securing the flows of key ecosystem services like food production and soil productivity and then one of the six WASCAL clusters deals with agricultural systems. Hence, there exists a link of research activities between the two institutions.

1.8 Description of the Study Area

The study area is located at Sadore village (between longitude 13º 02’12’’ N to longitude 13°15’00’’ N, and Latitude 2º 16’ 01’’E to latitude 2°17’ 00’’E). It is about 40 km south-east of the Capital Niamey in the Tillabéri Region of Niger. The Region is situated in the south of the country (Figure 1.1). It is in the Sudano-Sahelian zone. The hot dry season is long (from November to May) and the cropping season is very short (from June to October). Rainfall is highly variable with an annual average of 550 mm. The intensity of rainfall is very high with 50 % of the events having intensities exceeding 27 mm. h^{-1} and peak intensities of up to 386 mm. h^{-1} (Sivakumar, 1989). It has a very high potential evaporation which varies between 2000 and 4000 mm. $year^{-1}$. Daily temperature ranges between 25 and 41 °C (Nouhou, 2017). Further, soil type in Sadore is classified as a sandy siliceous isohyperthemic Psammentic Paleustalf in the

USA Soil Taxonomy. It belongs to the Labucheri type, characterized by a high sand content, low native fertility with low organic matter and low cation exchange capacity that limits nutrient storage and water holding capacity. These soils are generally very strongly to strongly acidic (pH 4·5–5·0), with aluminium comprising a high proportion (0·47) of the exchangeable cations. Soil water content at field capacity is 0·09–0·10 m3/m3 (Ibrahim *et al*., 2015).

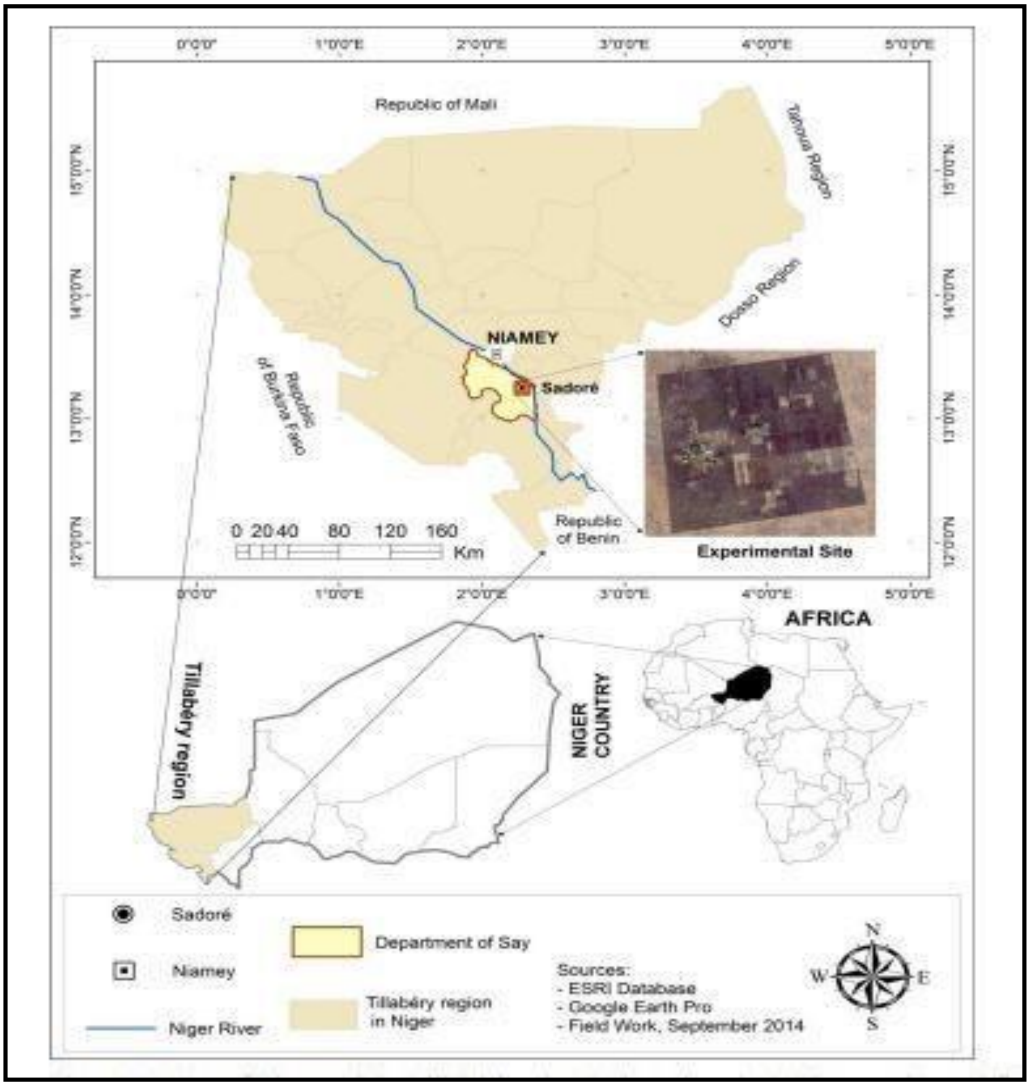


Figure 1.1: Location of the study area: Niger and Tillabery map (enlarged section). The experimental field is located near Sadore village: (Source: Nouhou, 2017).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Conceptual Review

2.1.1 Climate change and sustainable land management

Sustainable land management (SLM) techniques have tremendous potential for mitigation of greenhouse gases (GHGs) in particular from agricultural land. In fact, SLM strategies and practices are aimed at preventing land degradation and reducing deforestation phenomena. Similarly, farmers could have the ability of reducing GHG emissions and maintaining carbon stocks on the surface and into the soil with relatively low intervention costs and hence improving food production and living conditions (Kelly *et al*., 2013).

Further, it is verily possible to reduce carbon emissions from erosion and other soil degradations and to capture carbon from the atmosphere while conserving these soils when good agricultural practices are reinforced. According to FAO (2012), a combination of good practices can be used to ensure SLM. These practices include crop management, pasture management and natural rangelands, forest management, improvement of soil management and improved rainwater harvesting management. However, the potential contribution of agricultural land management for reduction of GHG emissions, if it is not yet recognized in clean development mechanism, this would not constitute a primordial factor allowing at the landscape scale and would not promote some mitigation projects that will fully attest to changes in land use planning. The potential mitigation of GHG emissions from agricultural land in Africa is estimated to exceed one thousand tonnes of carbon each year until 2030 as reported Terrafrica (2016).

2.1.2 Agriculture, climate change and mineral fertilizer use interrelation

According to IFA (2009), global food security and development goals cannot ever be achieved without fertilizer use. Indeed, the global industry of fertilizer does account for 2.5% of GHGs in which about 1.5% derives from fertilizer application. Hence, the fertilizer industries acknowledge the fact that they contribute to GHGs emissions mainly CO_2 and N_2O from the production and fertilizers utilization. Johannes (2015) indicated that the percentage of the undesirable environmental consequences of mineral fertilizers is alarming. Thus, this particularly affects man-made N by reducing the content of humus into the soil. Hence, this brings about soil acidification and raises emissions of N_2O so also GHGs, which are harmful to future crop production.

Further, this is confirmed by Yara (2017) who showed that fertilizer manufacture and also transportation, use and consumption of mineral fertilizers generate GHGs although, fertilizer use increases productivity and crop yields. The IPCC (2007) also revealed that the predicted consequences of climate change are huge to the extent that agriculture will be highly vulnerable and the rate of GHGs emissions of agriculture might be continuing rising with future food demands.

2.1.3 Soil nutrient dynamics

In the broad sense, nutrients refer to all material elements that are essential to biological functions. Among them, about 17 nutrients are essential for plants. Most importantly, Nitrogen, Potassium and Phosphorus are the primary macronutrients and the most needed by plants. Guo *et al.* (2012) reported that nitrogen levels in the soil are low but in the last few decades, the use of inorganic fertilizer had increased nitrogen levels as well as crop yields and water use efficiency. Moreover, Okebalama, (2014) estimated that soil nutrient depletion proportion is about 22 kg N, 2.5 kg P and 15 kg K ha^{-1}. $year^{-1}$ of arable land. Though loss of nutrients was estimated to contribute only 9 % of the total causes of land degradation which reduces soil capacity to increase food productivity. Particularly, in Sadore, Batiano *et al.* (2007) and Suzuki *et al.* (2017) confirmed that this depletion of N and P nutrients are a very great threat to crop production. However, recent findings in the long term experiment of the region showed that N and P nutrients significantly affect total dry matter and grain yields (Suzuki *et al.*, 2017; Akponikpè *et al.*, 2014).

Soil management practices have great impacts on soil nutrients dynamics and hence affect soil fertility. Most importantly, the technology of micro-dosing fertilizer application is widely recognized as a strategy of nutrient management in integrated manner so as to sustain agronomic productivity (Ibrahim *et al.*, 2016; Ibrahim *et al.*, 2015, (Ibrahim *et al.*, 2014, Rabi, 2013; Bationo *et al.*, 2012, Bagayoko *et al.*, 2011; Maimouna, 2010; Tabo *et al.*, 2006).

Nevertheless, Kapkiyai *et al.*, (1999) reported that some land management practices applied in Kenya have resulted in decreasing organic matter of the soil. About 557 kg C. ha^{-1}. yr^{-1} was obtained as the average proportion of loss by application of fertilizer and also by removing crop residues.

Avery (1995); Doran *et al*. (1996) and Adediran *et al*. (2004) all confirmed that the use of mineral fertilizer to support agriculture has proven a convenience. However, when it is applied, this results in a decrease of the organic matter(OM) content of the soil, which also reduces crop yield because of soil acidity and soil nutrient imbalance as stated by Ayoola & Makinde (2014).

Also, soil nutrient depletion is a great concern and hence become a serious threat with respect to agricultural productivity in developing countries (Tan *et al.*, 2005). Consequently, Ibrahim *et al*., (2016) pointed out the fact that microdosing fertilizer leads to an increase of risk of nutrient depletion in Sahelian sandy soils.

On the other hand, Ibrahim *et al.* (2015), confirmed that an increase of fertilizer application depth ranging from 5-10 cm gave a significant increase in terms of the root length density while the big depth of the application of fertilizer has given an increase of high yields. In addition to that, lateral root development in the context of micro-dosing affects also nutrient dynamics meaning that plants extract nutrients from the space between the planning hill which in the case of application of fertilizer micro-dosing does not receive any fertilizer. Hence fertility level of that space can soon be exhausted. Therefore, the impact of micro-dosing fertilizer on nutrient mining in long term trial becomes a striking issue that needs to be addressed (Bielders, 2015; Blessing *et al*., 2017).

2.1.4 Fertilizer use and nutrient imbalance

According to Chude *et al.* (2012), fertilizer application is generally considered in relation to their immediate effects on crop yields and often when their residual effects are ignored. If farming continues upon the same lands over years, residual effects of fertilizer treatments may considerably affect the soil chemical properties and consequently the yield of crops grown in later years. One of these residual effects is on the relative abundance of the cations in the soil subsequent to fertilizer application. There is evidence to show that availability of cation to crops may depend less on the absolute amounts of each cation present in the soil than on the balance existing between the various cations in soil solution. It is known that the use of ammonium-containing N-fertilizers in savanna environments results in the development of soil acidity, loss of cations and a redistribution in the relative amounts of the various cations in soil solution. In both the savannah and forest zones of Sahel, it has been observed that magnesium deficiencies in crops may be caused by absolute Mg shortage, but by excessive applications of potassium (Batiano *et al*., 2007; Chude *et al*., 2012).

Nutrient imbalance is accelerated by the use of incomplete fertilizers and by improper management of crop residues. Use of straight fertilizers (e.g. Urea) chosen primarily on the basis of short-term economic returns could aggravate the problem of nutrient imbalance in soils and must be discouraged.

Sommer *et al.* (2013) showed that soil nutrient mining is widespread, with a combined average depletion rate of N, phosphorus (P) and potassium (K) of 54 kg per hectare per year in SSA. While N is the most limiting nutrient for crop production, many agricultural soils in SSA are deficient in P, K, sulphur (S) and micronutrients as well, which makes balanced nutrient inputs critical. There is ample evidence showing that judicious use of inorganic fertilizers (right types and quantities of primary, secondary and trace elements) will maintain, and in some cases, improve soil fertility and crop yields for fairly long periods of continuous cropping system.

2.1.5 Factors affecting fertilizer use

Chude *et al*., (2012) described some major factors that considerably affect fertilizer use regarding agricultural productivity. Hence, five of these major factors are described as follows:

2.1.5.1. Crop factors

Fertilizer application cannot be effective unless the crop can respond to it. Certain crops need larger amounts of particular nutrients than others. Legumes, for instance, require large amounts of phosphorus and cereals require proportionately more nitrogen while most of tree crops and all root crops require more potassium. Improved varieties are more responsive to higher doses of fertilizer. Screening of crop varieties or ascension for tolerance or adaptability to a given mineral nutrient condition or stress in the soil is also an important factor affecting fertilizer use and consumption.

A plant can be referred to as nutrient efficient or inefficient. A nutrient efficient plant develops the natural capacity to respond to stress by altering its metabolism to make the element available. Whereas, a nutrient inefficient plant does not respond to measures to reduce stress and hence develops a nutrient deficiency effect.

2.1.5.2 Soil factors

The ability of soils to supply plant nutrients differs significantly from place to place and from time to time. Some physical soil properties, including soil depth, soil texture and soil structure underpin to its productivity. Any type of soil has its intrinsically productive potential. Appropriate applications of rates of mineral fertilizer might be beneficial to soils that have higher production potentiality but which are lower in fertility.

2.1.5.3 Climatic factors

In the region where rainfall is short, soils lose less from lixiviation and their natural fertility level is moderately high. However, this depends on water availability if fertility level needs to be much high. Soils of wet zones often lose much their essential nutrients via leaching and weathering. The quantity of water supply is suitable for high crop yield but nevertheless nutrient supplies are not acceptable.

2.1.5.4 Economic factors

Use of mineral fertilizer is encouraged but the increase of its price is a major problem. Increase in crop yield due to increased fertilizer applications follow the law of diminishing returns. Applications of optimum rates of fertilizers result in the greatest return per kg of nutrient applied. Further applications give progressively lower increases in yield.

Eventually, a point could be reached where an increase in the amount of fertilizers only increases yield enough to pay for the cost of this extra fertilizer.

2.1.5.5 Management factors

Increased crop yields usually require increased fertilizer inputs. Maximum yields depend on many factors including soil characteristics, abiotic factors, current and previous type of varieties, cropping history, type of mineral fertilizer use, tillage, and weeding.

2.2 Fertilizers

2.2.1 Definition and classification of fertilizers

Overall, fertilizers are substances, (mostly it refers to the mixture of mineral elements), intended to provide additional nutrients to plant which it needs so as to improve its growth and crop yield increase (Zodomé, 2012). Fertilizers are generally classified into three major types depending on nutrient proportion that form them as well as their nature (table 2.1).

Table 2.1: Fertilizers types and definitions

Types of fertilizer	Definitions
Mineral Fertilizers or artificial Fertilizers	Fertilizers of mineral origin which promote plant growth. They are produced by chemical synthesis, or through the exploitation of natural deposits of phosphate and potash. The concept of mineral fertilizer is opposed to organic fertilizer which is made from organic matter of either animal or vegetable origin.
Organic Fertilizers	Mixture of animal and or vegetable waste which contain nitrogen, phosphorus and potash, but the proportions are sometimes less important than in a mineral fertilizer (CNABio, 2013).
Organo-mineral fertilizers	Result from the mixture of mineral fertilizers and organic fertilizers. Fertilizers should contain at least 1% organic nitrogen (IFV, 2010)

Source: (N'Gone, 2014)

2.2.2 Soil nutrient requirements for plants

Knowing plant nutrient requirements helps to apply fertilizer in a reasoned manner and mostly to ensure optimal crop yield (N'Gone, 2014). Thus, for optimum plant growth, nutrients should be available in sufficient and balanced quantity (Chen, 2006). Moreover, plant needs water, sunlight, oxygen, carbon and also trace elements in the soil. These nutrients used by the plant come from soil, water or air (Wopereis *et al*., 2008).

Table 2.2 Roles of different nutrients to plants

Groups		Nutrients		Role
	Water component	Water	H	Structuring element (carpenter substance)
	Air component	Carbon	C	
	Water and air component	Oxygen	O	
Macro-elements or main components	Major Nutrients	Azote	N	Growth, formation of albumen and chlorophyll; " Growth accelerator "
		Phosphorus	P	Transformation of energy substances, training Roots , flowers and fruits development
		Potassium	K	Water management, plant health, stress resistance, cold resistance, favours the formation of reserves
	Minor nutrients	Magnesium	Mg	Formation of chlorophyll; photosynthesis
		Calcium	Ca	Construction and stability of cell walls
		Sulfur	S	Constituent of some amino acids, (component of the "albumen)
Microelements or trace elements		Iron	Fe	Chlorophyll formation, transformation of energetic substances (component of enzymes)
		Manganese	Mn	Photosynthesis (formation of chlorophyll) nitrates reduction
		Boron	B	Structure, division, differentiation of cells, transport of Carbohydrates
		Zinc	Zn	Formation of carbohydrates and albumen
		Copper	Cu	Formation of albumen, chlorophyll, enzymes
		Molybdenum	Mo	Transformation of nitrates into albumen, formation of Enzymes

Source: (N’Gone, 2014).

2.2.3 Effects of mineral fertilizers on the environment

Fertilizers play an important role in plant development. However, they can be harmful not only to the plant but also cause health and environmental risks. The intensive use of mineral fertilizers by agriculture is the major cause of groundwater and rivers contamination by nitrate release ($NO3^-$) which is strongly accumulated in the soil (Levallois and Phaneuf, 1992). In fact, when mineral fertilizers are applied in excess to the plant needs and if it reaches soil holding capacity, they are regarded as the major causes of the drinking water pollution (related to nitrates toxicity). Also, the eutrophication of freshwater and seawater through the leaching of soluble elements, either towards water table or towards streams by runoff.

In addition, soil pollution caused by artificial fertilizers leads to the destruction of living resources, physical environment and aquatic ecosystems imbalance via eutrophication (Keddal and N'dri, 2007).

2.3 Mineral Fertilizer Micro-dosing Review

2.3.1 Origin of fertilizer micro-dosing technique

The sandy soils of the Sahel region in Niger are often poor in nitrogen and phosphorus, both of them have a considerable influence on plant growth. In general, farmers use garbage and animal waste on crops or fields in order to improve soil fertility. However, a problem remains as these fertilizers do not act quickly and nutrients cannot be supplied to plants when they really need it (Giller *et al*., 1997).

According to JIRCAS (2012), the use of mineral fertilizers could be considered with the aim of solving the problem of accessibility of fertilizers for they have a very high price that farmers cannot afford these fertilizers in the Sahelian zones of the Niger. This makes it difficult for them to use large quantities.

As result of the current situation, the National Institute of Agronomic Research of Niger (INRAN), and ICRISAT Sahel Centre undertook a joint research with the aim of improving efficiently the use of mineral fertilizer for agricultural production and hence to reduce the costs of agricultural equipment for helpless farmers. Reports from this research revealed that applying little amount of mineral fertilizer near plant roots, made the technology possible to obtain better crop production than broadcasting the fertilizer in the farms, which was highly practiced by a large majority of farmers. This placement of small rate of mineral fertilizer was the starting point of the technique of manual placement of mineral fertilizer micro-dosing.

2.3.2 Description of mineral fertilizer micro-dosing

FAO (2012) described the manual fertilizer micro-dosing placement as a technique of placing small amounts of fertilizer at the planting hill. In Niger, this technique consists of manually put a pinch of fertilizer or a cap of bottle into the hills at the time of sowing, or close to the roots of plants during the growth phase.

JIRCAS (2012) confirmed that with regard to pearl millet, farmers space of 1 m x 1 m, and 10000 plant density are cultivated per hectare. Hence, the amount of fertilizer used in the micro-dosing is about 50000g per hectare since a dose is about 5 g. This amount of mineral fertilizer can be easily afforded by farmers.

Further, the effects of micro-dosage become obvious on the 15th day after planting, when the rains were sufficient (more than 15 to 20 mm approximately) and when the soil moisture content is sufficient. When the root system of the young shoots begins to develop, a small amount of fertilizer (compound NPK 15: 15: 15) is placed in some distant location (5 to 10 cm) from the roots. After this first application, a small amount of urea (1g. $hill^{-1}$) is applied about one month later and it is preferable to apply the mineral fertilizer after weeding and or thinning. In order to avoid work duplication, farmers often apply both seeds and mineral fertilizer together on the planting hill at sowing time. However, when rainfall is insufficient after sowing, the seeds end up losing their faculties of seedling which then have the opposite effect to prevent the growth of the plant(JIRCAS,2012).

2.3.3 Procedure of mineral fertilizer micro-dosing application

Appropriate procedure of mineral fertilizer micro-dosing technology is drawn with the following plates when it is used after sowing rather than at sowing time (JIRCAS,2012):

- ✓ **Step 1:** Before starting the application, first weeding and thinning should be perfectly carried out.

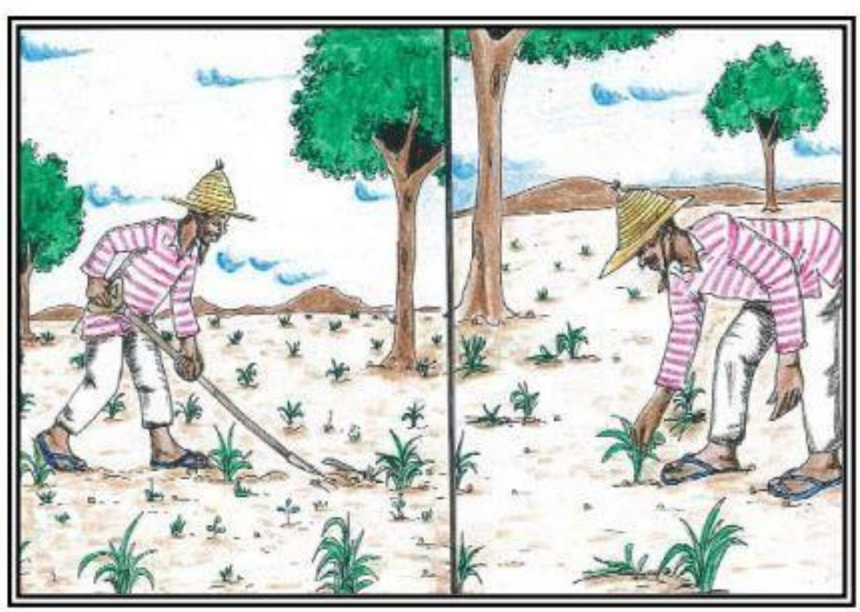


Plate I: Weeding and thinning conducted before the application of mineral fertilizer of micro-dosing (Source: JIRCAS, 2012).

✓ **Step 2**: Verification of soil moisture content after it has rained. Soil moisture should be as sufficient as possible. Hence, soil moisture content is checked by holding a piece of soil on the hand and hence if it hardens, that means soil moisture is sufficient so the soil is ready to receive mineral fertilizer at planting hill.

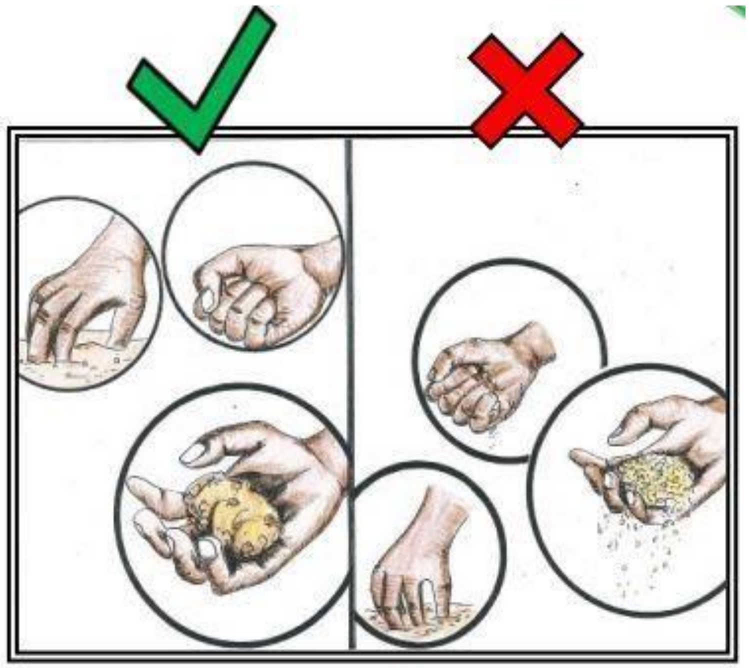


Plate II: Verification of soil moisture content before applying mineral fertilizer micro-dosing close to the planting hill (Source: JIRCAS, 2012).

✓ **Step 3:** Digging a small hole near to plant roots and then applying a pinch of mineral fertilizer (6 g. $hill^{-1}$ of NPK or 2 g. $hill^{-1}$ of DAP+ 1 g. $hill^{-1}$of urea).

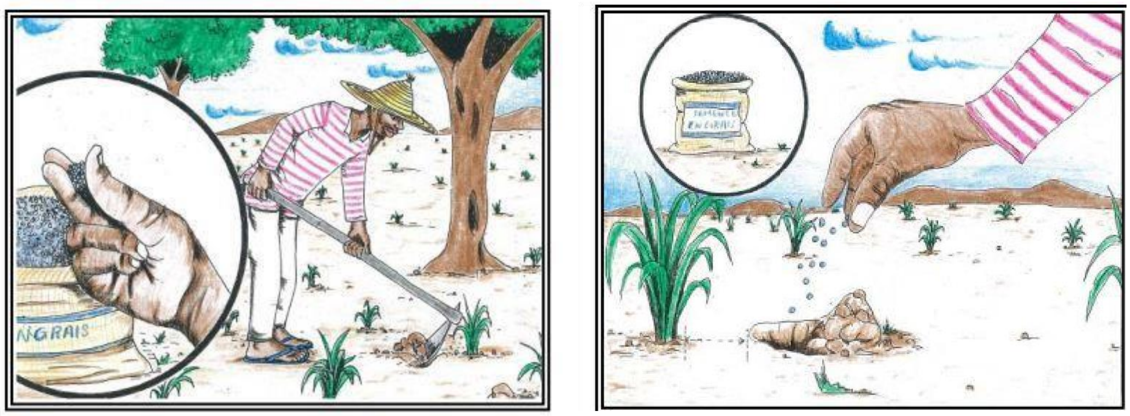


Plate III: Farmer digging a small hole and applying a pinch of mineral fertilizer micro-dosing (Source: JIRCAS, 2012).

- ✓ **Step 4:** After mineral fertilizer micro-dosing was applied, the hole is then well closed with soil.

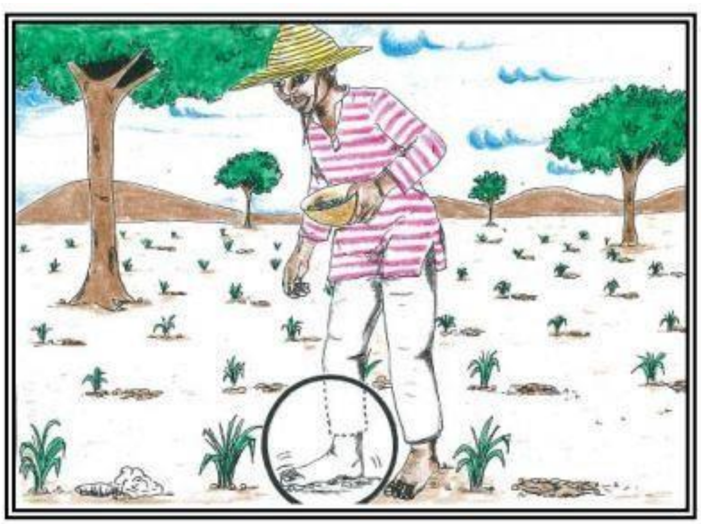


Plate IV: Farmer closing the hole after applying a pinch of mineral fertilizer micro-dosing (Source: JIRCAS, 2012).

- ✓ **Step 5:** Here we are, good production might be excepted after the 4 above steps were carried out.

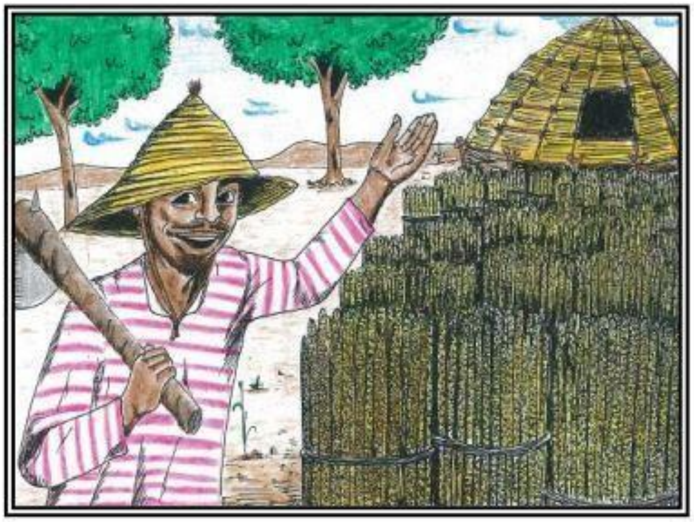


Plate V: Good production gotten by farmer with application of mineral fertilizer micro-dosing (Source: JIRCAS, 2012).

Moreover, mineral fertilizer micro-dosing is applied at sowing period (plate 2.6). Hence, the two methods are all used and appreciated by farmers.

Plate VI: Mineral fertilizer micro-dosing application at sowing time (Maimouna, 2010)

2.3.4 Some major merits of micro dosing application

According to FAO (2012) there exist several environmental and economic merits of micro-dosing technology**.**

- **Environmental merits**
  - A substantial increase in crop yields with a very low investment in mineral fertilizers;
  - Yields increase from degraded soils;
  - A more efficient use of fertilizers;
  - Coverage of phosphorus requirements in deficient soils;
  - A "boost" to plants at the start and early maturity protecting from drought of end of season;
  - A limitation of nitrogen losses by volatilization.

- **Economic merits**
  - Less financial investment for farmers;
  - Increased revenues through higher production;
  - Accessibility of technology to the most deprived farmers, given its low cost.

2.3.5 Empirical review of micro-dosing fertilizer application

Many studies showed that mineral fertilizer micro-dosing significantly impacts on total dry matter increase and cereals, which improves productivity (Ahmed *et al.*, 2016; Ibrahim *et al.*, 2015; Ibrahim *et al.*, 2014; Rabi, 2013). Many authors have experimented the use of 2 g per collar of DAP (18-42-0) and 6 g of NPK (15 15 15) including crop residues or excluding crop residues are applied (Ibrahim *et al*., 2016, Maimouna, 2010).

Ibrahim *et al*. (2015) discovered that the application of 2 g per hill of DAP (18-42-0) and 6 g of NPK (15 15 15) showed an increase of 86% and 79% of grain yield. In addition, micro-dosing fertilizer contributed to an increase of pearl millet yield with about 240 to 300 kg ha^{-1} of grains on sandy soils across Sahel.

Further, Rabi (2013) estimated the effect of micro-dosing application of NPK on two sesame varieties. She found that the micro-dosing application had positive effects on yield parameters of the two varieties of sesame.

2.3.5.1 Effect of mineral fertilizer on millet yields

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; Ibrahim *et al.*, 2016). 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 in Ibrahim *et al.,* 2015). Research on mineral fertilizer strategies for increasing crop yields has, therefore, mainly concentrated on sustaining plant demands in N and P which are considered as the nutrients that limit crop yield (Bationo *et al.*, 2003).

Exchangeable K^+ is not often regarded as limiting nutrient of pearl millet productivity in Sahel zone of Niger, in part because of substantial potassium inputs from Harmattan dust (Herrmann *et al.*, 1996). However, Rebafka *et al.* (1994) showed bulky responses to K fertilizer when crop residue is applied. In addition, Voortman *et al.* (2004) pointed out the significance of K in clarifying spatial variability of plant growth.

Furthermore, after two-year of continuous fields under cultivation of millet in a long-term combined application of both crop residues and inorganic fertilizers in Niger, Hafner *et al.* (1993) observed the potassium deficiency in the soil limiting for optimal millet production. According to Fofana *et al.* (2008), application of phosphorus fertilizer alone led to gradually and significant grain and straw yields increase. Even though, several studies confirm the opinion that P availability is key for millet yield increase on fragile soils of Niger. Added to that, Michels and Bielders (2006) found that 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 point out that Nitrogen and P are key elements to millet production. The Nitrogen fertilization response of millet was palpable only if P is applied. As confirmation, Bationo and Ntare (2000) demonstrated that usual millet-cowpea rotation in Niger does not contribute to millet yields increase except with the addition of mineral N and P fertilizers. So, there is need to make the suggestion of a cropping system that will integrate millet-legume rotation as an adequate alternative for replenishing soil fertility on degraded soils.

Fertilizer intake in 55% of SSA countries including Niger is not up to 5 kg. ha^{-1}. Therefore, ICRISAT and other institutions have established fertilizer micro-dosing technology so as to inspire courage in farmers to use the technology (Abuja, 2006).

2.3.5.2 Effect of fertilizer micro-dosing on crop productivity

Several studies have tested the instant millet and sorghum effect to fertilizer micro-dosing in the Sahel (Ibrahim *et al.,* 2015). Abdou *et al.* (2012) stated that significant increase in pearl millet yield resulting from tactical placement of 4 kg P per hectare of NPK (15-15-15) and DAP at planting hill. In Niger, studies have revealed that application of 6 g. $hill^{-1}$ NPK fertilizer per hill can increase millet yields twofold (Bationo and Buerkert, 2001) and possible economic return might be obtained after using the technique (Hayashi *et al.*, 2008; Tabo *et al.*, 2011). It was assumed that the positive effect of fertilizer micro-dozing can possibly be assigned to a root-growth which stimulates the P fertilization effect as Aune and Bationo (2008) and Buerkert and Schlecht (2013) formerly stated. There is, however, no empirical evidence that explains the root growth dynamics under fertilizer micro-dosing. There is, therefore, a need to elucidate the root mechanisms underlying the growth enhancing phenomena of the fertilizer micro-dosing 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 applying of 0.9 g N together with 0.4 g P in NPK to each hill builds up about 10 to 20% of millet plant’s total N requirements. 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. However, some researchers (Aune and Coulibaly, (2015); Buerkert and Schlecht, (2013)) think that this assertion is an overstatement. According to these authors, the increase in grain yield reported from micro-dosing ranging from 240 to 300 kg. ha^{-1} on Sahelian soils across West African environmental conditions (Bagayoko *et al.*, 2011) is not high enough to push the alarm on mining effect of the technology. From their estimation, 100 kg. ha^{-1} of grain yield as an increase, removes roughly 2 kg. ha^{-1} of N and 0.3 kg. ha^{-1} of P). This nutrient reduction ratio is lower than the amount of N and P that are applied in 60 kg NPK ha-1 (15-15- 15) 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 (Ibrahim *et al.,* 2016). 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 decline following continuous application of only mineral fertilizer (Schlecht *et al.*, 2006).

2.4 Review on Pearl Millet

2.4.1 Origin of the crop

Many authors agreed to attribute the origin of pearl millet to West Africa. Pearl millet was domesticated for about 4,000 to 5,000 years ago along the Sahara. The main centres of millet diversity are located in Africa where there are wild cross species. It is *P. purpureum,* or elephant grass, a perennial tetraploid species probably resulting from the crossing of an unknown diploid millet with an ancestral form of *P. americanum* and *P. monodii*, an annual diploid species that frequently crosses into the wild with cultivated millet producing vigorous and fertile hybrids called *Shibra* in Niger (Brunken, 1977; Renard and Kumar, 2001).

Marchais, (1993) indicated that the greatest morphological diversity is found in West Africa, the centre of origin of pearl millet, and it is divided into two categories: early maturing varieties after 75 to 100 days, and late types that reach mature after 100 to 150 days. No wild form is found outside Africa. On the other hand, ICRISAT database (2017) pointed out that pearl millet does go by several common names, including *Bulrush millet*, *Babala*, *Ddukn* (in the Sudan), and *Bajra* (in India). It appears to have emerged and first been domesticated in the Sahel zone of West Africa, which is known to be the crop's main center of diversity. It has been grown in Africa and on the Indian subcontinent since prehistoric times. Recent archaeological and botanical research has confirmed the presence of domesticated pearl millet in the Sahel of Northern Mali about 4,500 years ago. Cultivation subsequently spread to Northern India, where it took root just 5 centuries later, and over the next 5 centuries after being introduced, it spread throughout the country. During this same period, cultivation also spread across Eastern and Southern Africa. Records show that farmers began growing pearl millet in the United States in the 1850s, and the crop found its way to Brazil as recently as the 1960s (ICRISAT data base,2017).

2.4.2 Taxonomy of pearl millet

Brunrken (1977) reported that pearl millet belongs to:

Genus: *Pennisetum*

Family: *Poaceae (alt.Gramineae)*

Subfamily: *Panicoideae*

Tribe: *Paniceae*

Subtribe*: Cenchrinae.*

2.4.3 Agronomic description of pearl millet morphology

Maiti and Bidinger (1981) described the morphological structure of pearl millet as follows:

The plant has an erect habit and its height ranges between 0.5 and 4 meters depending on the varieties. The root system is fasciculate (having a seminal root and many self-propagating roots). Root system development is significant, up to 180 cm at harvest and allows better adaptation of the climatic and edaphic conditions of the semi-arid zones. The stem is rigid and the internodes are full. Basic internodes stretch out the last and then are the shortest. The bottom nodes are able to give secondary tillers as well as tertiary tillers. All tillers are not fertile: 1 to 7 tillers per plant reach to produce. The alternate leaves having parallel nervures fit into the stem and the tillers close to the nodes. These leaves have a sheath enclosing the stem and a lanceolate limb. The nervures are well developed and prevent the limb from bending. The limb carries stomata on both sides.

The inflorescence consists of a very dense and apical panicle that has a cylindrical shape. Its length and diameter vary according to the variety (15 to 140 cm for the length and from 0.5 cm to 4 cm for the diameter). The panicle (false ear) is formed of a rigid rachis carrying pedunculated and grouped spikelet in clusters. Each spikelet has two flowers: the top flower is hermaphrodite or female, generally fertile, while the lower flower is sterile or male. Overall, a few days off between blooms males and females favour cross pollination.

The fruit is a long caryopsis of about 4 mm and having multi colors.

2.4.4 Growth and development of millet

(Maiti and Bidinger, 1981) drew the different growth and development phases of pearl millet as follows:

The growth cycle of pearl millet can be divided into three phases: the vegetative phase, the reproductive phase and the filling phase of the grains.

- **Vegetative phase (from 0 to 50 DAS)**

The vegetative phase starts at the seedling period of the plant and continues until the initiation of the panicle. The germination of millet is hypogeous and if there exist favourable conditions, it occurs about 24 hours after sowing. The seed emergency takes place with the appearance of the first leaf, that is 4 to 5 days after sowing (DAS). At the end of seed emergence, the buds of all leaves have appeared and for early varieties, 6-7 leaves are already developed. The seedling develops its primary root system and forms many adventitious roots. Tiller development starts 15 days after emergence and continues for 10 to 20 days. The tillers produced late, will not form ears or their ears will not mature. The size of the plant remains reduced for the lengthening of the internodes has not yet occurred. During the vegetative phase, biomass accumulation mainly concerns leaves and roots. The initiation of the panicle is marked by the elongation of the apical dome and allows the entry into the next phase.

- **Reproductive phase (50 to 75 DAS)**

The leaves spread and the first ones at the bottom of the plant dry out. When the plant is going to speed, the internodes extend from the bottom. The tillers follow the same phases as the main stem with an interval over time. In this phase, biomass accumulation concerns the stem in addition to roots and leaves. The panicle develops spikelet, flowers, stigmas, anthers and it emerges two or three days later when flowering has occurred. The female flowers bloom first, starting with the top of the panicle and gradually descending, followed by the male flowers. Five to six days later, flowering and pollination of the panicle are completed.

- **Grain filling phase (> 75 DAS)**

This phase begins when the flowers of the main inflorescence are fertilized and continues until the maturity of the whole plant (main stem and tillers). Biomass accumulation appears mainly in caryopses but also continues in other parts because the tillers are stunted. The senescence of the leaves continue till there are only the last 2 or 3 leaves still green. The grains through a milky phase, a waxy phase and a glassy phase before reaching the physiological maturity, which is about 20 to 50 days after flowering depending on the variety.

2.4.5 Role and importance of pearl millet production

Pearl millet represents the sixth most important cereal crop worldwide; it is an important food crop as far as food security is concerned mostly for the semi-arid tropics countries. According to FAO, (2001) in Bachir, (2008), pearl millet often accounts for more than 30% of total cereal production and its total production in the world is around 31 million tonnes per year and approximately 40% (nearly 1/3) of the worldwide production comes from Africa and West Africa provides about 80%.

The crop plays a larger role in African agriculture and economy than in other parts of the world. Farmers usually produce pearl millet first for self-sufficiency. (Omar and Batourou, 1987). The low yields are due to some factors such as poor soils, poor skills of the farmer and rainfall scarcity.

It is usually an extensive crop, practiced without irrigation or mineral fertilizer use. The yields under such conditions range between 200 and 500 Kg. ha^{-1}. Pearl millet production is often for human consumption. It is consumed as traditional foods in the form of bread, porridge, couscous, and pancakes. It is also used in some areas for the production of alcoholic beverages and animal feed. Further, in developed countries (USA, Australia, South America), millet occupies a very marginal place, and serves as a high quality forage crop, and aviary bird feed. (Renard and Kumar, 2001).

It is estimated that millet accounts for about one-third (1/3) of the total consumption of food grains in Burkina Faso, Chad and The Gambia, about 40% in Mali and Senegal and more than 2/3 in Niger (FAO, 2012). In addition to that, pearl millet used for animal feed is not significant compared to other uses and other cereals. Only about 10% of worldwide use of millet goes into animal feed (FAO, 2012).

2.4.6 Ecological requirements of pearl millet

Pearl millet tolerates drought, and supports low soil fertility as well as acidic soils and high temperatures. (Bachir, 2008). However, clay soils are not favorable for pearl millet, which has a preference for light, sandy loam soils over heavy soils. The soil must be well drained and aerated. Further, deep soils, rich in organic matter provides higher crop production (Bachir, 2008).

According to Renard and Anand (2001), pearl millet tolerates an average temperature of 28 ° C during all its vegetative stages. The most favorable temperatures range between 27 ° C and 30 ° C; it is a plant whose germination and flowering stages are sensitive to low temperatures. Pearl millet is light demanding in at all phases of its development, so that even too much mutual shading can diminish its productivity.

Rainfall is very important for this crop depending on the duration of the cycle: Early maturing pearl millet is grown in low rainfall areas (350 to 600 mm) with a 75 to 100 days' cycle whereas late maturing pearl millet variety is grown in the wettest areas (600 to 1000 mm) with a cycle of 110 to 150 days. Most of pearl millet varieties are grown in zones where rainfall range from 200 to 800 mm which spreads over a period of 3 to 6 months. Moreover, this crop requires fulfillment cycle before the end of the rainy season (Mahalakshmi *et al*., 1987).

2.4.7 Main limiting factors of pearl millet production in Sahel

It is very difficult to list all pearl millet constraints since they are complex and plenty.

Thus, according to Scheuring (1980), in some areas of Mali, losses due to down mildew can reach 40% of production. Mc Intire (1982) reported that losses of 27-37% in Niger Republic due to several factors, including *Raghuva* and *Shibra*.

Pearl millet yields, even for improved varieties, remain poor because of harsh climatic conditions, especially in the Sahelian zone. The growth of millet is rather due to the expansion of cultivated area, which means that technological innovations have not had a significant impact on crop productivity. (Spencer and Sivakumar, 1987). Low productivity of pearl millet is therefore mainly due to the following factors: climatic conditions, especially inadequate and poor distribution of rains; soil conditions related to soils low in organic matter and nutrients and finally the plant material itself which, while being well adapted to the conditions of the environment, has a low production potential. (Oumar *et al*, 1987).

2.4.7.1 Abiotic factors

- **Edaphic factors**

Soils used for pearl millet growth are mainly low in organic matter and other nutrients (Stoop *et al*, 1982). These soils are mostly sandy and poor in phosphorus, and sometimes lateritic; the clay content is always low and has poor quality (kaolinite). They are shallow with low exchange capacity and tend to get encrusting. At the onset of the rainy season, soil temperatures are often high and frequent sandstorms result in the burial of young seedlings resulting in poor crop establishment.

- **Factors related to agricultural management practices**

Farmers in Sahel are poorly equipped and they use archaic instruments for almost the entire agricultural operations. The percentage of farms equipped with suitable equipment is very low (around 30% in Mali and less than 10% in Niger). Thinning is seldom practiced because of lack of time, resulting in significant competition in the hills. A simple delay of 7 days in the first weeding can cause a loss of 10% on the yield stated (Matlon, 1983).

Therefore, improvement in farming techniques allows to increase the pearl millet production by 40% (Siband, 1983).

- **Climatic factors**

According to Maimouna (2010), climate in the Sahelian zone is characterized by a clear contrast between the dry season and the rainy season which lasts from 3 to 5 months. In all countries, cumulative rainfall tends to decrease over the years from north to south. The rainy season is generally characterized by a great variability with regard to the distribution and the height of the rains, particularly at the beginning and at the end of the season. It is in this area in which millet cultivation is particularly important and it is common to do three sowing as result of a bad installation of the cropping season.

2.4.7.2. Biotic factors

- **Phytopathological factors:**

Downy mildew or millet leprosy is probably the most dangerous disease of millet in the Sahel (Mbaye, 1993). Millet is the main host plant of the fungus (*Sclerospra graminicola* (Sacc.) Schroet), responsible of downy mildew. Before heading, diseased plants first have a yellow fading of their foliage that can appear very early on young plants. In case of early or severe infection, the plants are stunted or die. At earing, the attacked flowers change, in part or entirely, into leaves with production of deformed ears. They are sometimes called "witches brooms". The affected ears thereafter become black and swollen.

The Black rust is also due to a fungus *Moesziomyces penicillariae* (short) Vanty (formerly called *Tolyposporium penicellaeiae* Brief) (Zangre *et al.*, 1993). It is the second most important disease after mildew. The mushroom attacks mainly the ovaries before pollination by pollen grains. At fruiting, the attacked flowers are replaced by globular spores filled with black powder.

Selvaraj, (1980) showed that Ergot (*Claviceps fusiformis*) is rare in the Sahel, and occurs in wetter areas (Gambia, Ghana) while Black rust (*Iolyposparium penicillaria*) is the second most important disease in Africa, but has less damage to local crops.

- **Weed factors:**

Weed control is an important component to tackle crop yield decrease. Crop losses due to weed were estimated to about 25% (Tampa, 1983).

Apart from the classic weeds common in rain fed crops, the following species bring about serious effects:

Shibra (*Pennisetum stenostachyum*) is the adventitious form of pearl millet. It comes from a cross between pearl millet and wild millet. Through a mimicry mechanism, this adventitious form manages to escape weeding. *Shibra* plants are easily identifiable in the farm at harvest, they give ears having poor quality (Niangado,1989).

Striga (*Striga hermanthica*) responsible for more than 60 to 70% yield reduction in millet in the Sahelian zone. (N'doye, 1984). It is a weed plant with purple flowers, parasite that lives at the expense of pearl millet. This specie is present in all over millet production zones in Niger and cause serious damage to the crop (Mbaye, 1993). The seeds of *Striga hermonthica* give out a very tenuous radicle which must be quickly fixed on a host root (less than 96h) under threat of degenerating. After fixation, the seedling of *Striga hermonthica* sets up a conical sucker which penetrates into the tissues of the host root.

- **Entomological factors:**

Pearl millet is attacked by several species of insects belonging to various orders. In general, they are distributed throughout the Sahelian zone, but their incidence varies each year from one site to another.

Head millet miner (*Helliocellus albipunctella*) has since become, one of the greatest flail of this crop in the Sahel zone in 1974. The head millet miner swarms especially on the sown areas which sowing was carried out very early throughout the season following a very early rain.

Farms sown later (June to July) are usually much less infested. Farmers can record losses due to the action of this pest, reaching the half of their harvest. Studies conducted by Krall *et al.* (1995) in the Sahelian zone revealed that millet yield losses due to this pest varies from 8 to 95 Kg. ha^{-1}. The damage is due to young larvae which perforate the glumes and eat away at the interior of the flowers. The older larvae cut the floral peduncles and those of fruits thus causing their drying (Dabre, 2008).

The biological control is the most method used to address this flail. It consists of the use of predatory and parasitoid arthropods (insects and spiders) and pathogens (viruses, bacteria, fungi, nematodes and protozoa) or their derivatives to control insect pest populations. Studies conducted on the biological control of *Heliocheilus albipunctella* from Joannis, it is appeared that ectoparasitoid *Habrobracon hebetor Say* (Braconidae) was the most effective for the limitation this pest (Bal, 1992).

- **Other predators**

Granivorous birds cause a real problem in many Sahelian zones. Their attack varies from one year to another and they are also responsible of the low yields observed in early pearl millet maturing. The species *Quelea quelea* or *red-billed* worker is the most important species (Rachie and Majmudar 1980, Pradat 1962). Some pearl millet cultivars (*Sarakoua* in Niger and *Konatiné* in Mali) are considered to be tolerant to birds' attack.

- **Socioeconomic factors:**

These constraints are mainly based on the low purchasing power of farmers, the difference between the price of agricultural inputs and millet and poor access to equipment and agricultural credits are factors that limit the adoption of new technologies for higher crop production.

Added to that, the insufficiency of the transformation units of pearl millet is also considered as socioeconomic factors (Bachir, 2008).

CHAPTER THREE

3.0. MATERIALS AND METHODS

In this research work, the methodology adopted was in two major steps i.e. fieldwork (collection of soil samples from the long term experimental site) and lab work (laboratory analyses).

3.1. Instrumentation for Data Collection and Analysis

Several instruments were used in order to collect soil samples in the field. Thus, two (2) graduated tubes (from 0-10; 10-20 and 20-40cm) were used for collecting soil composite samples. Pails served to gather elementary soil samples so as to mix them and get the bulk samples. Besides, any composite sample was put in small labeled plastic bag (plate VII). The table 3.1. shows the list of different instruments used for soil sampling.

Table 3.1: List of equipment used for soil survey

Equipment used	Purpose of use
2 graduated tubes	Collection of soil composite samples
Pails	To mix elementary soil samples
Small pots	To gather elementary soil samples
Small labelled plastic bag	To put the soil samples
Drill tool	Field furrow in order to delimit the plot
Tissue bags	To collect and put all the composite soil samples

Source:(Author, 2017).

Plate VII: Soil samples in small labelled plastic bags (Author, 2017)

3.2. Plant Material

Pearl millet [*Pennisetum glaucum*] was the plant material of this study.

Local Sadore was used from the long term experiment.

❖ Local variety (local Sadoré) or "Haïni kirey", native to western Niger. It is large, late maturing (about 90 to 100 days from sowing to harvest). It gives long ears and is currently cultivated by farmers in the region.

Table 3.2: Characteristics of the Local Sadore

Observations	Local Sadore Variety
Days to flowing	55
Plant height(cm)	240
Length of the ear(cm)	60
Ear diameter (cm)	8
Weight of ear (Kg. ha^{-1})	3650
Weight of grain (Kg. ha^{-1})	1450

Source: (Maimouna, 2010)

3.3 Treatments and Experimental Design

The treatments and experimental design set out by the institute were as follows:

The experiment was arranged in a randomized complete block design (RCBD) with three replications. The treatments combination was the factorial combination of (a) four different nutrient management options (control, 30kg.ha^{-1} of composite fertilizer NPK (equivalent to 9 kg N ha^{-1} , 4 kg P ha^{-1} and 7.47 kg K ha^{-1}) , 60kg.ha^{-1} of NPK and 20kg.ha^{-1} of DAP(equivalent to 4 kg P ha^{-1} and 3.6 kg N ha^{-1}) corresponding to 2g. hill^{-1} + 10kg.ha^{-1} of Urea corresponding to 1g. hill^{-1} at elongation stem period), (b) two genotypes of pearl millet (Sadoré local variety and HKP variety), (c) three planting densities (Density 1= 5000 hills/ ha); spacing = 1.5m x 1m; Density2 = 10 000 hills/ ha); spacing = 1mx1m and Density3 = 15 000 hills/ ha); spacing = 0.8m x0.8 m). The use of these micro-dosing proportions is 6 g NPK hill^{-1} and this rate constitutes the current micro-dosing fraction endorsed in the study area (Tabo *et al.,*2011). Plot dimensions were 6m x 6m and the gross dimension of the experiment was 64 m x 55 m = 3569 m^2. Then, between row spacing was 1m whereas between replication spacing was 2m and the useful plot size is 25 m^2.

For the present research, regarding the change in soil nutrient dynamics (objective 1 and 2 of the study), a sub-set of the treatments from this long-term experiment was used and due to logistical constraints, only some treatments were identified for this sampling so as to limit bulky lab analysis. Hence, only one factor was considered and the treatments were also laid out in an RCBD. The factor is mineral fertilizer with two nutrient management options (0 input (control), 60kg.ha^{-1} of NPK corresponding to 6g. hill^{-1} of NPK (15-15-15). The treatment combination consisted of (a) local variety of pearl millet (local Sadoré), (b) density (1 x 1 m) and (c) 60kg.ha^{-1} of NPK. Hence, in the experiment, 12 plots were identified.

3.4 Soil Sampling

This study profited from data that were initially collected in the experiment being carried out since 2008 where agronomic data and soil data are collected on yearly basis. Before trial layout in 2008, initial soil samples were collected from each replication. After every two years, samples collection was carried out in each individual plot (plate VIII) but between hills was the sampling point. In the present study, in addition to composite samples collected between the planting hills, 4 planting hills were selected randomly on which the same core of samples were collected. The samples were collected on 12th May 2017 as the actual soil nutrient content of the experimental soil.

For the samples collection a graduated aluminum tube was adapted and used as soil sampling auger.

Plate VIII: Soil sampling positions in the experimental field (Author, 2017)

In total, 36 soil samples [2(planting hill + between hill) ×2(control plots + 60 Kg. ha^{-1}) × 3 replications×3cores samples= 36] were collected and three cores samples were considered: 0 – 10 cm; 10 – 20 cm and 20 – 40 cm.

3.5. Soil Analysis

Prior to the analyses in the lab, drying of soil samples was done and thereafter 2mm sieve was used to sieve the samples. The analyses of these samples were carried out at the soil laboratory of ICRISAT Sahelian Centre Sadore. Further, pH-H_2O, soil organic carbon (SOC), total N, available P and exchangeable cation K^+ were the chemical parameters chosen in order to achieve the objectives of this study. The following laboratory procedures were used to analyze the samples.

3.5.1 Soil pH

To analyse pH, potentiometrical measurement in the suspension of 1:2.5 soil water mixture was used: (Van Reeuwijk,1993). Ten gram (10g) portion of soil was weighted into a beaker and 25ml of distilled water added. The suspension was stirred in mechanic manner and allowed to stand for 30 minutes after which the pH in water was measured. Before the measurements, the pH meter (Hanno Instruments Ltd, Corrollton, Texas) was calibrated using buffer solutions of pH 4 and 7.

3.5.2 Determination of Soil Organic Carbon (SOC)

Organic carbon content of soil was determined using Walkley-Black procedure described by Van Reeuwijk (1993). This involves a wet combustion of organic matter with the mixture of potassium dichromate ($K_2Cr_2O_7$) solution and sulphuric acid. Five gram (5g) portion of air-dried soil was weighted into a 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 (20ml) of concentrated H_2SO_4 (95%) was 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 was added. This was followed by the addition of 10 ml of concentrated (85%) orthophospheric 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 of organic Carbon (OC) was calculated as follows:

$$\%OC = M \times (V1 - V2/S) \times 0.39 \times mcf \qquad (3.1)$$

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= 3×10-3 × 100% × 1.3

3 = equivalent weight of carbon

1.3= compensation factor for the incomplete combustion of the organic matter.

3.5.3 Determination of soil total nitrogen

The determination of total nitrogen was made with the digestion method of Kjeldahl described by Houba *et al*., (1995). Thus, 1.0 g of soil portion was put in a Kjeldahl digestion flagon of 75 ml and then 2.5 ml of Kjeldahl catalyst (mixture of 1-part Selenium powder + 10 parts $CuSO_4$ parts $NaSO_4$) were added and mixed carefully. The stirred mixture was placed on the hot plate and heated to 100 o 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 mixture was heated again at 330^{o}C for hours till pure and neutral digest was gotten. The volume of the solution was made up of 75 ml with disinfected water. Clear aliquot of the sample and blank were pipetted and put into auto-analyser Technicon AAH (Pulse Instruments Ltd, Saskatoon, Canada) for the determination of the total nitrogen. The total nitrogen percentage was calculated as follows:

$$\% \ Total \ N = \frac{(a-b) \times 75}{weight \ of \ sample \ (g)} \times 100 \qquad (3.2)$$

where:

a= N content of the soil sample

b= N content of the blank

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

75 ml= final diluted volume of digest

3.5.4 Determination of soil available phosphorus

Soil available P determination was done with Bray No.1 method (Bray and Krutz, 1945) as described by van Reuuwjik (1993). Four gram of air-dried soil (2mm sieved) was weighted into flasks of 100ml volume (two blanks and a control soil sample were included) and 14 ml of Bray No.1 solution were added. The two mixed together were then shaken for about 5 minutes on a shaker mechanic device, allowed to stand for 2 minutes and then centrifuged for 5 minutes at 3000 rpm and filtered through a Whatman No. 42, filter paper. Five milliliters (5 ml) portion of the solution (sample) was pipetted into a volumetric flask of 25 ml followed by the addition of four (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 allowed to stand for at least an hour for the blue colour to develop to its maximum. Standard series containing 1.2, 2.4, 3.6, 4.8, 6.0 mg L-1 P were also prepared and treated similarly. The absorbance was measured was measured on the spectrophotometer (Wagtech Projects, Ltd, UK) at 882 nm. The extractable P (mg/kg) was calculated as follows:

$$P = (mg\ kg\text{-}1\ soil) = \frac{(a-b) \times 14}{s \times mcf} \qquad (3.3)$$

Where:

a = mg L-1 P in the sample extract

b = mg L-1 in the blank

S = air-dry weight of the soil sample in gram mcf = moisture correction factor.

3.5.5 Determination of exchangeable K^+

The determination of exchangeable K^+ is done like for other Exchangeable bases. First, these K^+ were extracted by the ammonium acetate (NH4OAc) 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 considered 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 was then added and the volume of the solution was made up of 50 ml with distilled water. Exchangeable K^+ by flame emission spectrophotometry (FES) at wavelengths 766.5. The standard series 0, 2.5, 5, 7.5 and 10 mg L-1 were used for K. The concentration of K^+ was calculated as follows:

$$K^{+}(cmol_c kg^{-1} soil) = \frac{(a-b)\times 10 \times mcf}{10\times 20.04 \times s} \quad (3.4)$$

Where:

a = mg L-1 of K in the diluted sample b = mg L-1 of K in the diluted blank

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

3.6 Pearl Millet Yield Components

The experiment is being planted every year with the first important rain (rainfall equal or higher than 20 mm). Hence, planting date (Table 3.2) depends on the time that sufficient rainfall is recorded. To study pearl millet performance, the following parameters were recorded on yearly basis in the long term experiment: planting day, emergence day, day to tillers appearance, days to flower, days to maturity, days to harvest, number of head harvested, head weight per plot, grain weight per plot, stover weight per plot. The crop was harvested at maturity as border rows were eliminated at each side of the plot to avoid border effect. For this research, we focused on crop yield components in order to achieve the objective 3. The stover yield as well as the grain yield, total biomass and harvest index were considered. A total of nine (9) years yield data from 2008 to 2016 were used so as to evaluate the effect of nutrient management options over the years of pearl millet.

Rainfall data from 2008 to 2016 were processed and used with the aim of enhancing the interpretation of the results of crop yield components.

Table 3.3: Planting dates and the cropping seasons of the long term experiment

Cropping seasons	**Planting dates**
2008	18th June
2009	13th June
2010	04th June
2011	20th June
2012	12th June
2013	02nd July
2014	01st June
2015	09th June
2016	15th June

Source: (Author, 2017).

3.7 Procedures for Data Analysis

3.7.1 Calculation of changes of different soil nutrient contents

After the lab analyses of the samples, data were processed using Excel. The mean of the 3 soil depths was considered for the statistical analysis of all the parameters. Hence, the change in soil nutrients was calculated using the following formula:

$$Change\ in\ N, P, K(\%) = \frac{ASNC - INSC}{ASNC} \times 100 \qquad (3.5)$$

where:

ASNC: Actual soil nutrient content of the experimental soil,

ISNC: Initial soil nutrient content of the soil experimental.

3.7.2 Crop yield measurement during harvest period

First, fresh weight of leaves and stems tied in sheaves is measured in the field by using mechanical scales weighing 50 kg (graduations of 200 g) fixed on tripods. A coin- sample of the sheaf was also weighed using a smaller scale (5 or 10 kg, graduations at 20 g). Thereafter, the dry weight of the sample of leaves and stems was measured after this one was left to dry several days. This has served later to determine the dry weight of leaves and stems.

Knowing that the harvest area of a useful plot of the experiment is 25 m², the dry weight measurements enable the calculation of different yields components:

- **The stover yield (Yp)** was calculated with the following formula:

$$Yp(kg/ha) = \frac{Psp(g)}{Pfp(g)} \times PFtot_{b(g)} \times \frac{10}{25} \qquad (3.6)$$

Where:

Yp= Stover yield

Psp= dry weight of the leaf and stem sample

Pfp= fresh weight of the leaf and stem sample

PFtotb= total fresh weight of the sheaf of leaves and stems per plot

- **The grain yield (Yg)** was determined by using the following formula:

$$Yg(kg/ha) = \frac{Psg(g)}{Pfb(g)} \times PFtot_{b(g)} \times \frac{10}{25} \qquad (3.7)$$

Where:

Yg= grain yield

Psg= grain weight of the sample of ears

Pfb= fresh weight of the sample of ears

PFtotb= total fresh weight ears per plot

- **The yield of bunch of ears**(Yb) was determined using the following formula:

$$Yb(kg/ha) = \frac{Psg(b)}{Pfb(b)} \times PFtot_{p(g)} \times \frac{10}{25} \qquad (3.8)$$

Where:

Yb= *grain weight of the sample of ears*

Psb= *fresh weight of the sample of ears*

Pfb= *total fresh weight ears per plot*

- **The total biomass** was calculated using the formula:

$$B(Kg/ha) = \sum Yb; Yp(Kg/ha) \qquad (3.9)$$

Where:

B= total biomass

Yb= *grain weight of the sample of ears*

Yp= Stover yield

- **Harvest index** was calculated using the following formula:

$$HI(\%) = \frac{Yg(Kg/ha)}{B(Kg/ha)} \qquad (3.10)$$

Where:

Yg= grain yield

B= total biomass

Thereafter, statistical analysis was done using GENSTAT v.9.2 (Lawes Agricultural Trust, 2007) where analysis of variance was hence performed by using a general treatment structure (in Randomize Blocks) for both crop yield data and soil data. Differences among treatments were considered at error probabilities ≤ 0.05.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

In this chapter the findings of this research work are presented in form of tables and graphs which are explained and discussed to achieve the objectives of the study.

4.1 Soil Properties of the long term Experimental Field

Table 4.1 and 4.2 show the initial characteristics of the long term experiment site. Based on FAO guidelines (1992) for interpretation of soil analysis, it is concluded that the SOC content and extractable P (P-Bray 1) across the soil depths were all very low with 2.2 g C. Kg^{-1} soil and 2.7 mg kg^{-1} respectively. The average of total Nitrogen (N) content was low with 179 mg kg^{-1} and soil pH (H_2O) was strongly acidic. The texture class was determined using textural triangle(FAO,1992).

Table 4.1: Initial physical and chemical characteristics of the long term experiment site in 2008

Parameters	Soil depth(cm)			Mean values
	0-10	10-20	20-40	0-40
Sand(g. kg^{-1})	94.6±0.2	76.5 ± 4.4	73.2 ± 4.8	-
Silt(g. kg^{-1})	2.4±0.1	8.3 ± 2	8.3 ± 1.2	-
Clay(g. kg^{-1})	3.0±0.2	15.2 ± 2.8	18.5 ± 3.9	-
Textural class	Sandy	Sandy loam	Sandy loam	-
pH(1: 2.5 H_2O)	5.1±0.03	5.2±0.08	5.1±0.06	5.1±0.05
Org C(g.Kg^{-1})	3.3±0.004	1.9±0.01	1.4±0.005	2.2±0.02
Total N(mg. Kg^{-1})	280±13	153±5	105±3	179±6.33
Available P(mg. Kg^{-1})	3.7±0.3	2.3±0.1	2.1±0.2	2.7±0.2
K^+(mg.Kg^{-1})	107±40	43±6	33±5	161±17

±Standard error.

4.2 Current Soil Nutrient Measurements of the Experimental Site

Table 4.2 illustrates the actual soil nutrient content of the experiment site (objective 1 and 2 of the study).

It is observed that pH values have decreased compared to the initial values. On the plots applied with NPK as micro-dose, the mean soil pH was 4.6 while the mean of pH before trial layout in 2008 was 5.1. This indicates that the soil is getting acidic regardless of the application of the micro-dosing mineral fertilizer. The trend is similar concerning the SOC which remains constant (2.0 C g. Kg^{-1} soil) as average despite the fact that crop residues were every year left in to the experiment site every year. It is concluded that this may be due to the production of biomass which export much nutrient instead of sequestering into the soil.

Nevertheless, the dose of available P has increased over time with application of mineral fertilizer micro-dosing with respectively 3.1 mg. Kg^{-1} and 6.1 mg. Kg^{-1} for the between hills and the planting hills. An increase of available P at the planting hills compared to between hills was observed. This could be due to the accumulation of P in the soil over time.

Table 4.2: Current characteristics of chemical parameters of the experiment site

	Sampling position	pH-H2O	P Bray1 (mg. Kg^{-1})	Total N ($mg.Kg^{-1}$)	OC (g. Kg^{-1})	K^{+} ($mg.Kg^{-1}$)
Control	Between hill	4.7±0.13	2.7±0.1	141.6±5.094	1.0±0.006	45.3±4.16
Control	Under hill	4.8±0.092	2.5±0.08	157.3±10.13	2.0±0.02	62.8±5.903
NPK(6g.hill)	Between hill	4.6±0.04	3.1±0.25	151.6±10.66	2.0±0.009	44.0±4.5
NPK(6g/hill)	Under hill	4.6±0.06	6.1±0.1	170.5±11.44	2.0±0.011	72.8±0.53

±Standard error.

4.3. Change in Soil Nutrients in the Experimental Plots

4.3.1. Change in soil pH (H2O)

Figure 4.1 shows the change of pH-H_2O values of the experimental soil.

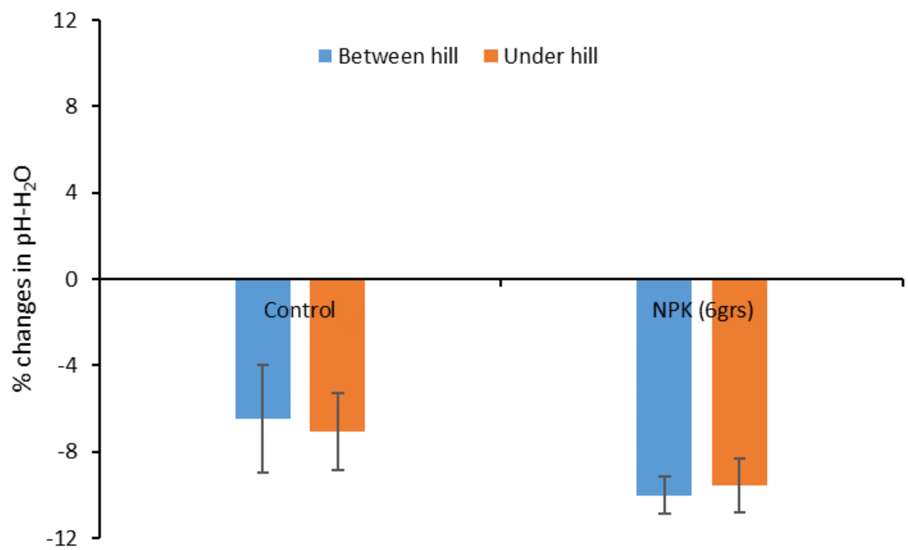


Figure 4.1: Change in the pH (H2O) values from 2008 to 2017of the experimental site as affected by treatments

Due to the long-term cropping in the experimental plot, soil pH-H_2O decreased in both the control as well as that applied with NPK (15-15-15) as micro-dose. In the control plot as well as in the fertilized plots, the amplitude of the change in pH-H_2O was similar whether the sample was collected between the planting hills or on the hills. When compared with the control plots, soil acidity has increased significantly more on the planting hill than between the hill ($p \leq 0.05$). Change in soil pH was 7.06% for the control and -9.57% for the plots treated with NPK. The higher negative percentage of this change indicated that a possible acidification of the soil experiment occurred. These results confirm the findings obtained by Rabi (2013) who showed a variation of pH-H_2O value of about 0.45 after applying 1g. $hill^{-1}$ of NPK at planting hill of sesame.

4.3.2. Change in total Nitrogen

Figure 4.2 illustrates the change in total Nitrogen that occurred in the experimental field.

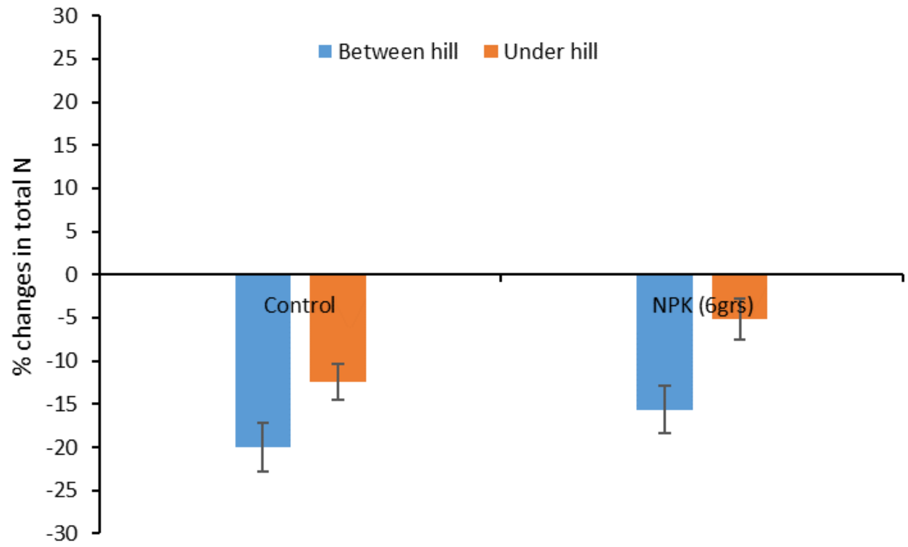


Figure 4.2: Change in total nitrogen content of the soil as affected by treatments

Results showed that soil total nitrogen content has dropped over the year of cropping in both the control plots and the plots receiving NPK as micro-dose. This negative change in total Nitrogen was more important around between the hills than on the hills regardless of the treatment received (figure 4.2). The amplitude of nitrogen content drop was lower in the plots applied with NPK than in the control plots. Application of NPK has lowered the amplitude of nitrogen content drop on the planting hill (5.11%) compared to the control plot (-12.45%) indicating partial replenishment compared to the between hill space and the control. Therefore, micro-dosing option significantly ($p \leq 0.05\%$) affected Nitrogen content.

The negative change might be due to the mobile character of N into the soil and to the soil nutrient export from biomass production of pearl millet.

These results are in line with the work of (Buerkert, 1995 and Bandoum, 2005) where they showed that fertilizer micro-dosing caused nutrient export initially present in the soils.

These findings also agree with the results found by Ibrahim *et al*., (2016), they found that fertilizer micro-dosing with (2g DAP and 6g NPK) had a negative effect on both partial and full nutrient balance pearl millet field.

Added to that, the work of Rabi (2013) confirmed that total dry matter of sesame local variety seriously exported partial nutrient balance with about 21.9 g/kg N with application of NPK at hill.

However, Ibrahim *et al*. (2016) confirmed that a combined use of fertilizer micro-dosing along with manure had a positive partial nutrient balance. Similarly, this indicated that pearl millet used significantly much more nutrients from the native soil nutrients. On the other hand, the highest percentage of change observed at between hill may be due to the root length density of pearl millet that permit to the plant to look for nutrients far from the hill. This resulted in root length density behaviour that pearl millet adopted so as to benefit from nutrients where they are concentrated (Ibrahim *et al.*, 2015). With such nutrient mining character of fertilizer micro-dosing, cropping system could not be quite sustainable meaning that the technology cannot sustain the nutrient requirements of pearl millet over time.

4.3.3. Change in extractable Phosphorus (P-Bray1)

Figure 4.3 shows the change in extractable phosphorus content of the experimental soil from 2008 to 2017.

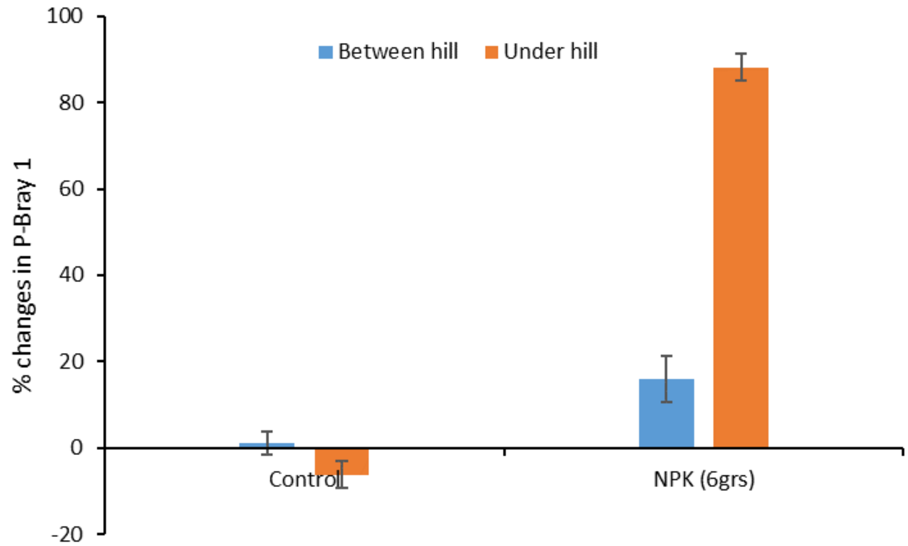


Figure 4.3: Change in extractable Phosphorus content of the experimental soil as affected by treatments**.**

Higher and positive changes were observed in plots where NPK was applied compared to the control particularly on the planting hills (88.19% vs -6.27%). In both the control and the fertilized plots, positive changes were observed in available P in soil at between the planting hills. This is an indication that even though P export through biomass production has occurred in both treatments, P accumulation has happened in the plots applied with NPK. Presumably P mobilization from the soil pool may have occurred that was more important on the planting hills. Research has shown that pH, Fe, Al and Ca concentration as well as soil texture and organic matter significantly affect P availability for the plant (Mkhabelaa and Warman, 2005).

In acidic soils and particularly with sandy structure like the one of our experiment (table 4.1), with up to 47% aluminium saturation (Fatondji *et al* 2006), it is expected that P immobilization occurs at pH lower than 5. In the sampled plots, soil pH has dropped from 5 to 4.8(figure 4.1). This low pH observed should have favoured P to be trapped into the soil complex. From the graph above (figure 4.1) on pH, we observed that the soil has become more acidic with application of the NPK. However, we noted that in the same plots there are much more plants available P with time. Yet, many studies confirm the opinion that P availability is regarded as a cornerstone for millet yield increase on a fragile soils of Niger (Bielders,2006).

The study presume that the present result needs additional analysis focusing on soil biological activity to be better understood.

Giroux and Tran (1994) demonstrated that in addition to soil chemical and physical properties, biological properties of soil have influence on Phosphorus behaviour.

4.3.4. Change in exchangeable K+

Figure 4.4 illustrates the change in exchangeable K^+ of the experimental field.

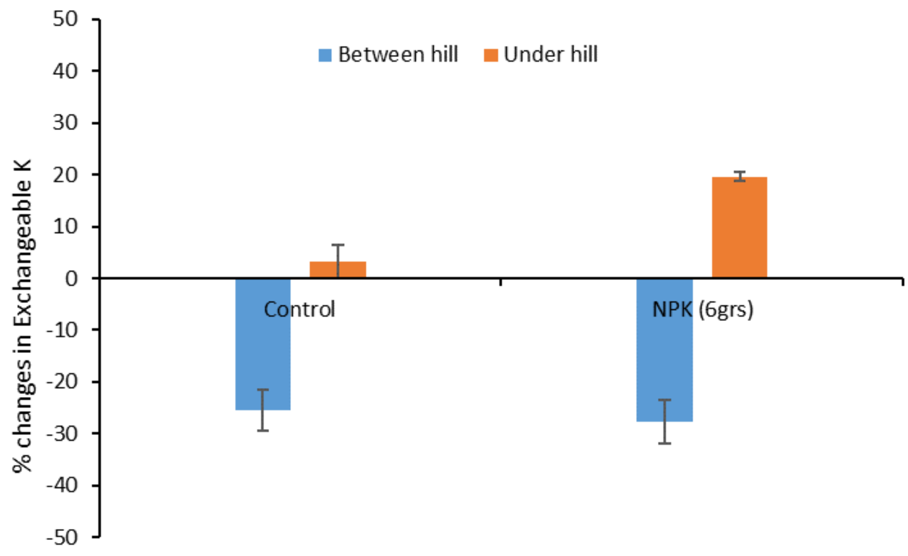


Figure 4.4: Change in exchangeable K+ content of the experimental soil as affected by treatments**.**

The results showed a positive change on the planting hill and it is significantly higher in plots amended with NPK (6g) at planting hill than in the control plots with 19.64% and 3.18% respectively in micro-dosing plots and the control plots. Difference between soil sampling positions is significantly different. The change is however negative in between hill with respectively -34.6% and -25.59% in fertilizer micro-dosing plots and the control plots. The positive change in exchangeable K^+ means that this nutrient is gradually stocked in the soil with the application of NPK, 6g over time. Nevertheless, the positive change was also observed in the control plots. This indicates that the accumulation of exchangeable K^+ is not only from the nutrients applied.

However, the native Sahelian soils in Sadore comprise a high percentage of exchangeable cations such as K^+, ca^{2+}(West *et al.*, 1984).

4.3.5. Change in soil organic Carbon

Figure 4.5 shows the change in organic Carbon of the experimental soil.

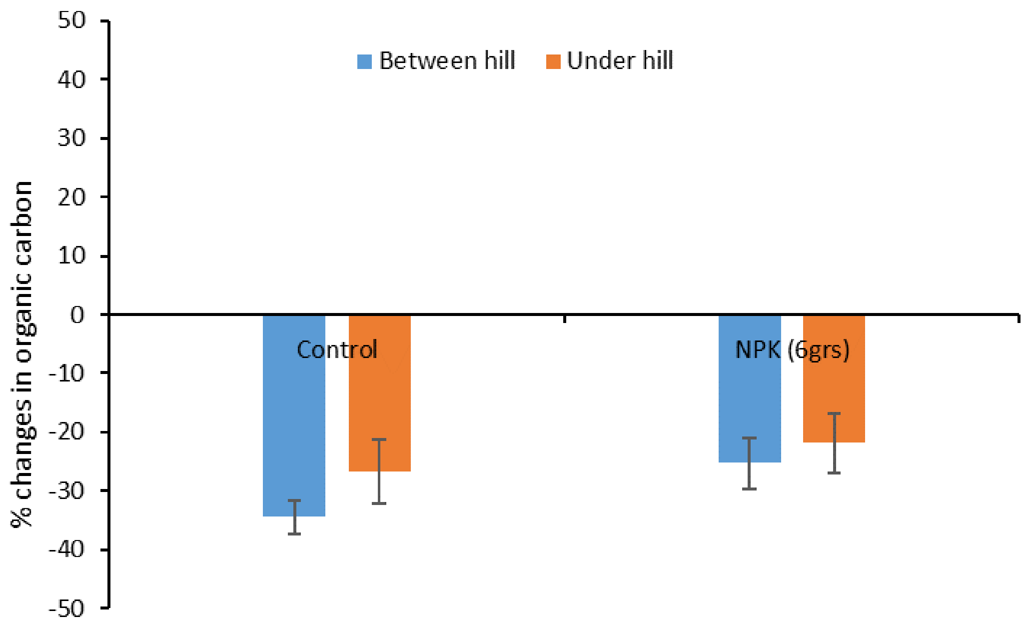


Figure 4.5: Change in the of organic Carbon content of the experimental soil as affected by treatments

The proportion of change in organic Carbon was negative both at planting hill and in between hills. The trend observed is similar to that of soil pH. Results showed that the change was a bit lower in micro-dosing plots compared to the control plots with respectively -21.85% and

-26.71% of change in organic Carbon.

The same applies to the between hill where the change was negatively greater in the control plots (-34.46%) compared to the micro-dosing plots (-25.29%). Nevertheless, no significant difference ($p \leq 5\%$) between treatments and soil sampling position was observed.

Though crop residues are usually left in the experimental field over the years, the study showed that the change in organic Carbon was relatively negative. First, this could be as result of the effect of the production of biomass from the soil. Secondly, this might be due to the fast mineralization of OM over time as it is Sahelian sandy soil which is fragile and inherently infertile. Hence its organic matter rate is very low (<1%). Most importantly, lack of application of organic manure over time in the experimental field can exacerbate the drastic decrease of organic Carbon in the long term. Consequently, Ibrahim *et al.*, (2015) indicated that use of the combination of organic manure with fertilizer microdosing promises in the long term an increase of pearl millet yields as well as efficient use of limited nutrients such as soil organic Carbon in Sahelian cropping systems. Additionally, Ibrahim *et al.*, (2016) confirmed that the nutrient depletion is the great consequence of the export of nutrients of crop residue.

4.4. Effect of Mineral Fertilizer Micro-dosing on Pearl Millet Yield Components over the Years

4.4.1. Rainfall distribution during different cropping period

The figure 4.6 shows the cumulative rainfall obtained during cropping periods ranging from 2008 to 2016.

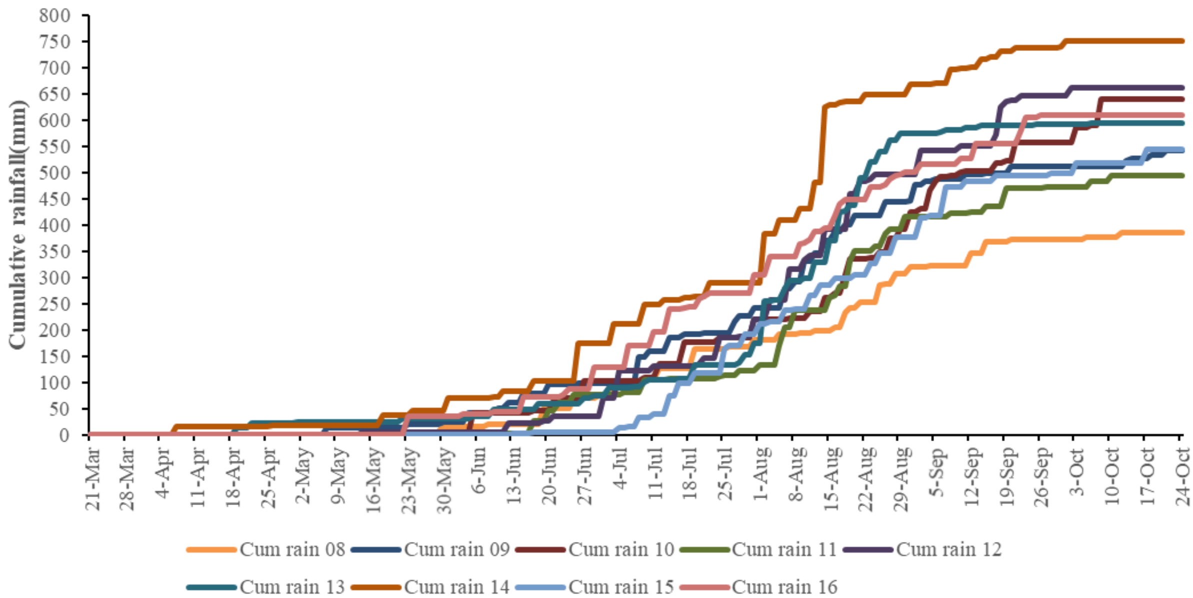


Figure 4.6: Rainfall distribution during different cropping period from 2008 to 2016

The rainy season in Sadore often starts at the beginning of June. The cumulative rainfall recorded in the first year of the experiment was 387 mm whereas in the following year 2009, the total rainfall has increased with a total of 542 mm recorded. In 2014, the highest total rainfall was recorded compared to the others years with 752 mm. This rainfall was about 200 mm higher than the long term rainfall (551 mm) recorded in the experimental site (ICRISAT Climate service) from 1984 to 2014 as reported by Ibrahim *et al., (*2016).

Furthermore, it was observed that many dry spell periods of about two to three weeks occurred which coincided with pearl millet reproductive and grain filling stages. These dry spell periods have occurred mainly in the first five years.

4.4.2. Effect mineral fertilizer micro-dosing on Stover yield over the years

The third objective of the study was to assess the effect of mineral fertilizer micro-dosing application on pearl millet yield over the cropping seasons. So, figure 4.7 shows the trend of stover yield of different nutrient management options over years and the summary of analysis of variance on different crop yield components is shown in appendix B.

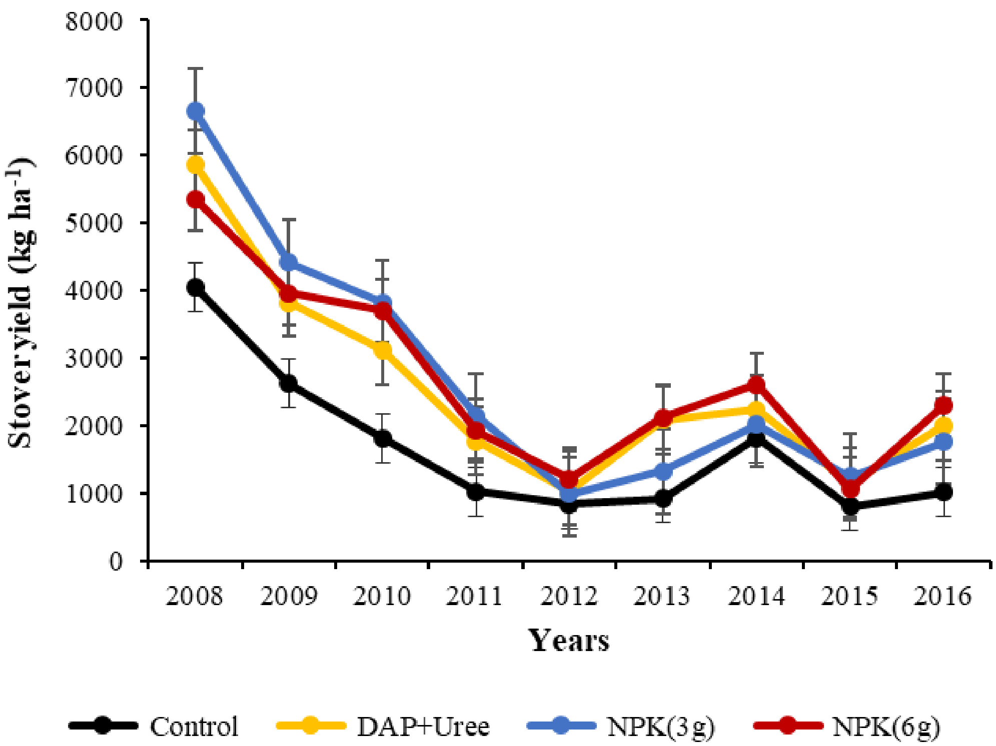


Figure 4.7: Stover yield of pearl millet as affected by treatments over the years

In 2008, both control plots and amended plots produced better stover yield than the other 8 years. The increase that occurred for the experiment started after a fallow when soil nutrient had been restored.

However, in the first five rainy seasons, stover yield has dropped in the control plots and in the three other plots treated with 2g DAP+ Urea, 3g NPK and 6g NPK as micro-dose. The stover yield of the control plots is always lower and tends to drop over the years than in the amended plots. The yield gap between the control and the amended plot increased over year, which is an indication that a certain level of production could be maintained with the technology even though the overall yield of the amended plots decreased. One of the reason that explains the drop of stover yield over the years in the amended plots was the possible acidification of the experimental site over the years inducing the effect of aluminum toxicity that affect particularly root growth (Kretzschmar *et al.*, 1991).

Further, the control plots produced average stover yield of 4053 Kg. ha^{-1} and 2627 Kg. ha^{-1} respectively in 2008 and 2009 while in the plots amended with 2g of DAP+ 1g Urea per hill, the stover yield was 5867 and 3827 Kg. ha^{-1} in 2008 and 2009. Among the three management options, plots amended with 3g. ha^{-1} of NPK produced higher stover yield (6667 Kg. ha^{-1}) in 2008 but stover yield of plots amended with 6g NPK has dropped less than the two other nutrient management options (3g per hill of NPK and 2g of DAP+ 1g Urea per hill). A significant drop of stover yield was also observed in 2012 rainy season with respectively 840, 1027, 987 and 1213 Kg. ha^{-1} in the control plots, 2g of DAP+ 1g of Urea, 3g NPK and 6g NPK plots.

This could be due to the short length of rainfall in this year and in addition to that, grasshopper attack occurred that led to a total replanting of the field. Most importantly, dry spell periods had happened in all the five years (figure 4.7). These results are in line with the work of Caroline (2006) who found that after applying organic and inorganic fertilizer as micro-dose to pearl millet, a significant drop ($P \leq 0.005\%$) of stover yield over three years of cropping seasons (1894 kg. ha^{-1} in 2003; 1232 kg. ha^{-1} in 2004 and 957 kg. ha^{-1} in 2005) was observed. She emphasized that such yield decrease was due to rainfall and its distribution as well as insect attacks and diseases. Hence, mineral fertilizer micro-dosing response to pearl millet is conditioned by water availability as indicated by Batiano *et al., (*2003). After the first five years, no further dropping of stover yield is observed again. Therefore, there was statistically no significant effect ($P \leq 0.005\%$) between the four nutrient management options.

4.4.3. Effect of mineral fertilizer micro-dosing on grain yield over the years

Figure 4.8 illustrates the grain yield of pearl millet over the years as affected by treatments.

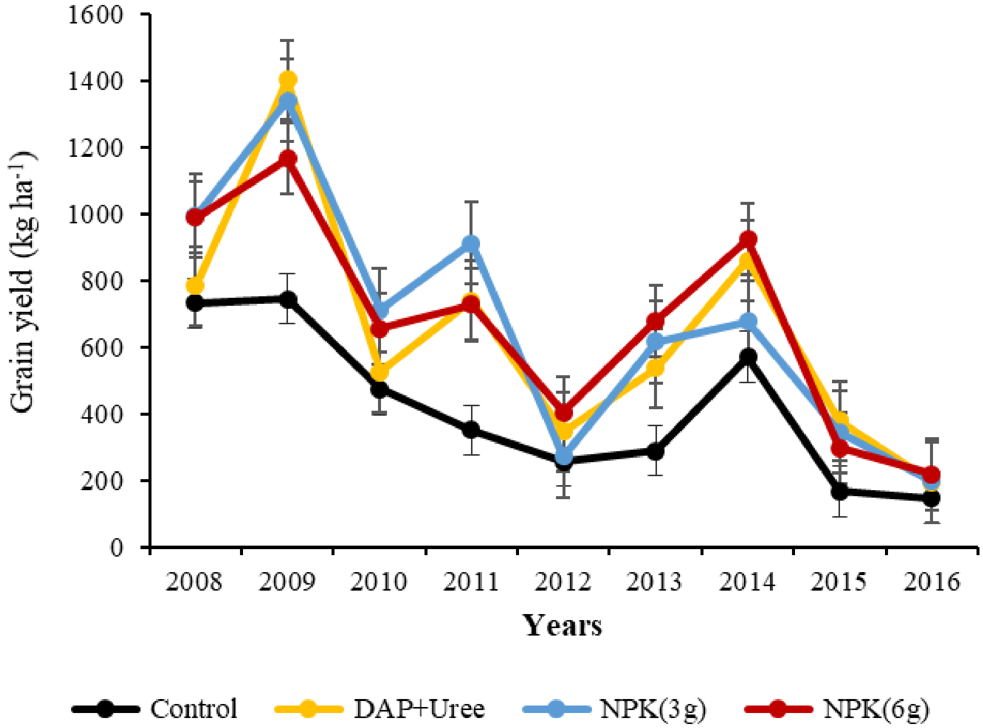


Figure 4.8: Grain yield of pearl millet as affected by treatments over the years.

Grain yield has increased from 2008 to 2009 regardless of the treatment types. In 2009, the control plots produced 745 Kg. ha^{-1} while 2g per hill of DAP+1g Urea plots, 6g per hill of NPK and 3g per hill of NPK plots produced respectively 1403; 1342 and 1166 Kg. ha^{-1}. In the following year i.e. 2010, grain yield dropped both in the control plots and in the plots treated with respectively 474; 525; 711 and 657 Kg. ha^{-1} with the control plots, 2g DAP+ 1g Urea plots, 3g NPK plots and 6g NPK plots.

From the observed trend we could say that fertilizer micro-dosing application resulted in significant yield increase compared to the control particularly in 2009.

However, in 2012, an important grain yield drop was observed in which an average of 256 Kg. ha^{-1} was obtained in the control plots and 346; 271 and 404Kg. ha^{-1} was respectively observed with the 2g DAP + 1g Urea; 3g per hill of NPK and 6g per hill of NPK plots. This lowest grain yield could be due to the short length rainfall regime recorded in this year and it might be as result of the grasshopper attack as well.

Moreover, in 2010, there was an occurrence of dry spell periods one in August (figure 4.6) during flowering stage of pearl millet and the second in September (figure 4.6) during grain filling stage. Hence these two stages are critical with regard to crop production.

Looking at the increase in grain yield in 2014 compared to the preceding year, this may be due to the influence of rainfall regime. Dry spell periods did not occur at the critical stage of millet growth. Grain yield obtained in this year is not significantly higher compared to the yield obtained in 2010 in which dry spell periods occurred. From this trend observed, this study concluded that nutrient management options were not the only limiting factor of yield drop. However, there is no significant effect of micro-dosing options at $P \leq 0.005\%$(table 4.4). Therefore, the rainfall pattern as well as other biotic factors affect grain yield over time. Regardless of these limiting factors that hampered pearl millet production, grain yield has decreased over years after the best record of 2009 (745 Kg. ha^{-1}; 1403 Kg. ha^{-1}; 1342 Kg. ha^{-1} and 1166 Kg. ha^{-1} respectively for the control plots, 2g DAP+1g Urea per hill, 3g and 3g NPK per hill plots). This explains that a lone application of mineral fertilizer micro-dosing could not maintain crop yield over time in low-input millet based cropping systems.

A combined application of manure and mineral fertilizer enhances increased grain yield in Sahel (De Rouw and Rajot (2004); Ibrahim *et al.*, 2014). Earlier manure application is favourable for root system development (Michels and Bielders, 2006) and allows faster initial leaf growth, thereby increasing water use efficiency and crop productivity (Bationo *et al.,* 1998, Shapiro and Sanders, 1997).

Similarly, in Sahelian cropping system, many studies have shown the importance of crop residue in the Sahel Region. Buerket *et al.,* (2000) reported 73% of millet grain yield increase was due to application of 2 t/ha of millet residue. Many studies have reported increased soil permeability and aggregate stability as well as increased water infiltration and water holding capacity, increased soil organic matter (SOM), pH, CEC and nutrient availability which can lead to sustainable yield and sustained soil fertility over time (Bationo and Mokwunye, 1991; Buerkert and Hiernaux, 1998).

4.4.4. Effect of mineral fertilizer micro-dosing on total biomass over the years

Figure 4.9 shows the total biomass of pearl millet as affected by treatments over the years.

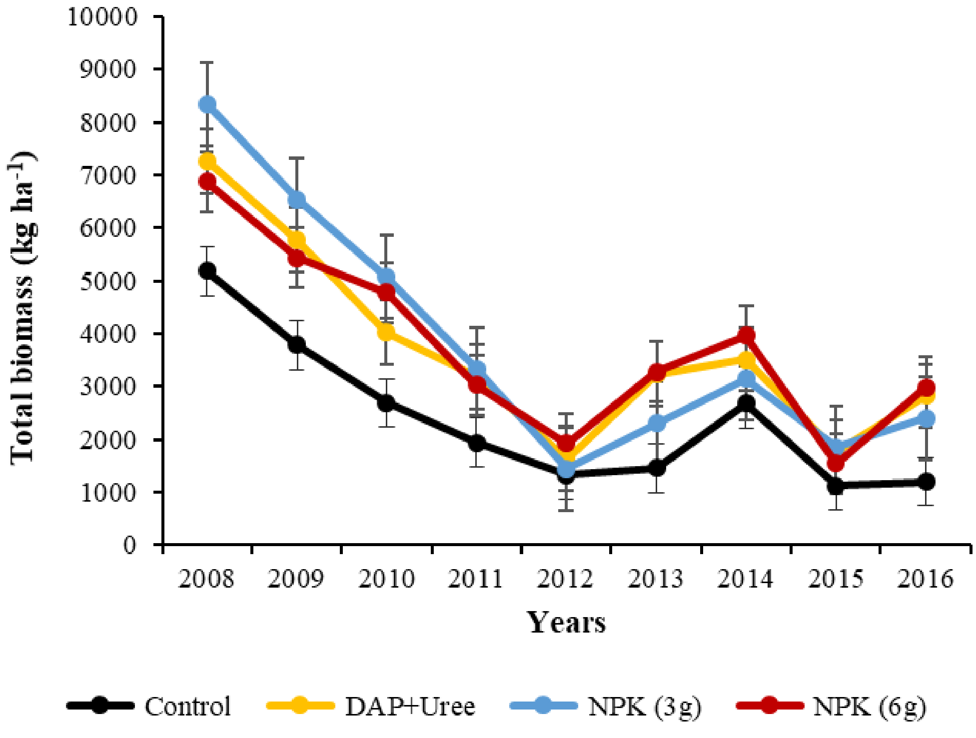


Figure 4.9: Total biomass of pearl millet as affected by treatments over the years

The trend observed was similar to that of the stover yield trend (figure 4.7). The control plots always produce lower yield than the amended plots and tend to drop over the years. In the first five years, total biomass has gradually dropped. In 2008, highest total biomass was recorded with 5178 Kg. ha^{-1} when plots treated with 2g DAP+1 g Urea, 3g NPK and 6g NPK per hill produced respectively 7264 Kg. ha^{-1}, 8342 Kg. ha^{-1} and 6870 Kg. ha^{-1}. After four years of cropping, the total biomass produced was 1327 Kg. ha^{-1} in the control plots and 1633 Kg. ha^{-1};

1443 Kg. ha^{-1} and 1930 Kg. ha^{-1} respectively in the plots amended with 2g DAP+1 g Urea, 3g NPK and 6g NPK per hill.

Therefore, yield drop was observed over time in all the plots amended with micro-dosing. Overall, this yield reduction over time might be attributed to fast nutrient release and organic matter decomposition reported for Sahelian conditions (Comfort, 2006; Batiano *et al.*,2007).

In addition to soil fertility decline, other environmental factors such as dry spell periods may bring about a drop of total biomass production over time. Recurrent dry spell periods in the first five years (figure 4.6) occurred coinciding with critical peal millet growth in this season including the grasshopper attack which has led to a replanting of the whole field.

4.4.5. Effect of mineral fertilizer micro-dosing on harvest index over the years

Figure 4.10 shows the harvest index as affected by treatments over the years.

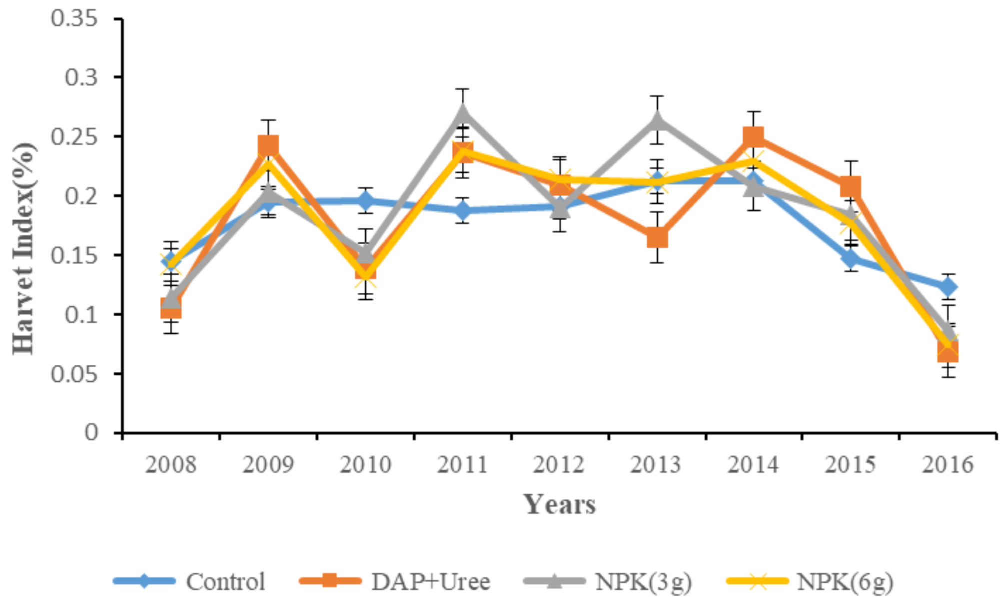


Figure 4.10: Harvest index of pearl millet as affected by treatments over the years.

The harvest index was affected by the mineral fertilizer micro-dosing over the years. At the beginning of the experiment it has increased and after two years it has decreased. The average of harvest index in 2008 was 0.14%; 0.10%; 0.11%; 0.14% respectively for the control plots, 2g DAP+1g Urea plots, 3g NPK and 6g NPK plots. Whereas it has increased in 2009 with an average of 0.19%; 0.24%; 0.20%; 0.22% respectively for the control plots, 2g DAP+1g Urea plots, 3g NPK and 6g NPK plots. The lowest harvest index observed in 2016 with respectively for the control plots, 2g DAP+ 1g Urea plots, 3g NPK plots and 6g per hill NPK plots was 0.12%; 0.07%; 0.08% and 0.07%.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The change in soil nutrients obtained in this study showed that fertilizer micro-dosing stimulates the export of soil nutrients which are initially present into the soil and that consequently encourages the soil impoverishment. Thus, fertilizer micro-dosing significantly affects soil nutrients in the long term. It was concluded that the trend of the change in soil pH-H_2O as well as in soil organic carbon, and in total nitrogen content were negative. However, only Phosphorus and exchangeable K^+ have presented positive changes. The study also concluded that the change in soil nutrient dynamics was better in the planting hill than from between hill. Therefore, the study concluded that the hill character greatly influences soil nutrient dynamics in long-term application of microdosing. Hence, it was clear that the soil nutrients dynamics at planting hill were better and different from soil between hill due to the hill application character. Therefore, it was deduced that fertilizer micro-dosing has led to a negative contribution with regard to partial and full soil nutrient balances instead of increasing such nutrient balance. Further, pearl millet yield dropped over time regardless of the treatments applied with mineral fertilizer micro-dosing. The stover yield as well as the total biomass showed similar trend over the years with a drastic drop during the first five years. Such decrease occurred as a result of soil fertility decline on the one hand and in another hand climatic factors and particularly dry spell periods and grasshopper attack have impacted negatively on crop yield. Therefore, we concluded that crop yield was not only affected by micro-dosing options but also environmental factors were included. Finally, for the technology to be sustainable in long-term, there is need to improve and maintain soil fertility and thus reverse nutrient mining of Sahelian sandy soils.

5.2 Recommendations

This thesis investigated the sustainability of fertilizer micro-dosing in the longer term. Thus, the study provided the change in soil nutrients over time which was relatively negative from 2008 to 2017 even at the micro-dosing hill. The recommendation emphasizes the sustainability of the fertilizer micro-dosing. On the basis of the findings of the study, some recommendations are drawn as follows:

1. Manure could be used in order to raise soil fertility of the Sahelian sandy soil of Niger Republic. Most importantly, that manure should be much more applied rightly at the place between hill so as to reduce the future impoverishment of the in between hill space. As a result, crop yield would be maintained and hence soil nutrient mining would be reversed.
2. Further research in the long-term should be undertaken to examine the effect of change in soil nutrients with other forms of micro-dosing options such as 2g of DAP and hence evaluating the best nutrient management options that could be used for a sustainable cropping system in Sahel.
3. Additional analysis focusing on biological properties of the soil should be undertaken so as to have better understanding of the soil nutrient dynamics so also the sustainability of the mineral fertilizer micro-dosing technology.
4. There is a need to use crop modelling such as DSSAT model so that it will help decision makers for better understanding of soil nutrient dynamics and mineral fertilizer micro-dosing effect on crop yield under the long-term effect of the technology.

REFERENCES

Abdou, A., Koala, S. and Bationo, A. (2012).Long-Term Soil Fertility Trials in Niger, West Africa. In Lessons learned from Long-term Soil Fertility Management Experiments in Africa, *105-120: Springer. The Netherlands*.

Abuja: (2006). Abuja Declaration on Fertilizer for the African Green Revolution. African Union Special Summit of the Heads of the State and Government. Abuja, 13 June 2006. 3.

Ahmed, Y. E. M., Osman, A. A. M., Makeen, M. A., & Suliman, T. E. A. (2016). Effect Of NPK Micro Doses Fertilizer On Leaf Area , Leaf Area Index And Pods And Hay Yield Of Six Genotypes Of Groundnut – *North Kordofan*, *5*(5).

Akponikpe P.B.I . (2008). Millet response to water and soil fertility management in the Sahelian Niger : experiments and modeling. Universite Catholique de Louvain.PhD Thesis.200.

Akponikpè, P. B. I., Gérard, B., & Bielders, C. L. (2014). Soil water crop modeling for decision support in millet- based systems in the Sahel : a challenge, *9*(7), 1700–1713. https://doi.org/10.5897/AJAR10.263.

Aune, J. B. and Coulibaly, A. (2015).Microdosing of Mineral Fertilizer and Conservation Agriculture for Sustainable Agricultural Intensification in Sub-Saharan Africa. In Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa, 223-234: *Springer. The Netherlands*

Ayoola, O. T., & Makinde, E. A. (2014). Soil nutrient dynamics , growth and yield of green maize and vegetable cowpea with organic-based fertilization. *Archives of Agronomy and Soil Science*, *60*(2), 183–194. https://doi.org/10.1080/03650340.2013.775422

Bachir B. (2008), Evaluation de l'effet des résidus de battage du Mill dans la culture associée Mill/Niébé, Université Abdou Moumouni /Faculté d'Agronomie Niger Mémoire de fin d'études, 61.

Bagayoko, M., Maman, N., Palé, S., Sirifi, S., Taonda, S. J.-B., Traore, S., & Mason, S. C. (2011). Microdose and N and P fertilizer application rates for pearl millet in West Africa. *African Journal of Agricultural Research*, *6*(5), 1141–1150. https://doi.org/10.5897/AJAR10.711

Bal A., (1992). Les principaux insectes du mil au Sénégal: importance du parasitisme et méthodes de lutte. *In* Lutte intégrée contre les ennemis des cultures vivrières dans le Sahel (1). Séminaires *&* colloques. Deuxième séminaire sur la lutte intégrée contre les ennemis des cultures vivrières dans le Sahel. Bamako, Mali, 4-9 janvier 1990. pp 13-23.

Bandoum Y. P., (2005). Effets de la fertilisation par micro dose sur la productivité du mil, les bilans des nutriments et de l'eau du sol au Niger. Mémoire de fin d'étude. Faculté d'Agronomie, UAM. 57p.

Bationo, A., Kihara, J., & Adesina, A. (2012). Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). *Improving Soil Fertility Recommendations in Africa Using the Decision Support System for*

Agrotechnology Transfer (DSSAT), (January 2012), 169–184. https://doi.org/10.1007/978-94-007-2960-5

Bationo, A., Mokwunye, U., Vlek, P. L., Koala, S. and Shapiro, B. I. (2003). Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone. In Soil fertility management in Africa: A regional perspective, 253–292 (Eds M. P. Gichuri, A. Bationo, M. A. Bekunda, H. C. Goma, P. L. Mafongoya, D. N. Mugendi, H. K. Murwuira, S. M. Nandwa, P. Nyathi and M. J. Swift). *Academy Science Publishers (ASP).*

Bationo, A. and Buerkert, A. (2001). Soil organic carbon management for sustainable land use in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems 61: 131-142.*

Bationo, A. and Ntare, B. (2000). Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. *The Journal of Agricultural Science 134: 277-284*

Bationo, A., Lompo, F., Koala, S. 1998. Research on nutrient flows and balance in west Africa : State-of-the-Art. Agriculture, Ecosystems and Environment, 71, 19-35.

Bationo, A. and Mokwunye, A. U. 1991. Role of manures and crop residue in alleviating soilfertility constraints to crop production: With special reference to the Sahelian and Sudanianzones of West Africa. *Fertilizer Research*, 29:117–125.

Bielders, C. (2015). Microdose fertilisation : a step on the ladder towards crop intensification in the Sahel ? *Earth and Life Institute*, 1–11.

Bindraban, P. S., Dimkpa, C. O., Nagarajan, L., Roy, A. H. and Rabbinge, R. (2014).Towards fertilizers for improved uptake by plants. *In International Fertiliser Society London, UK*, 3rd July 2014.

Bindraban, P. S., Jansen, D. M., Vlaming, J. and Groot, J. J. R. (1999).Land quality indicators for sustainable land management: The yield gap. Wageningen, The Netherlands: Research Institute for Agrobiology and Soil Fertility (AB-DLO)

Blessing, O. C., Ibrahim, A., Safo, E. Y., Yeboah, E., Robert, C., Logah, V., & Monica, U. I. (2017). Fertilizer micro-dosing in West African low-input cereals cropping : Benefits , challenges and improvement strategies. *African Journal of Agricultural Research, 12*(14), 1169–1176. https://doi.org/10.5897/AJAR2016.11559

Brunken J.N. (1977) A systematic study of *Pennisetum sect. Pennisetum* (Gramineae). *American Journal of Botany 64, 161-176. 37*

Buerkert A., (1995). Effects of Crops Residues, Phosphorus, and Spatial Soil Variability on Yield and Nutrient Uptake ofPearI Millet (Pennisetum glaueum (L.) R. Br.) in Southwest Niger. *PhD Thesis*.VerIag Ulrich E. Grauer, Stuttgart, 272.

Buerkert, A., Bationo, A. and Dossa, K. (2000). Mechanisms of Residue Mulch-Induced Cereal Growth Increases in West Africa11 Dedicated to Horst Marschner and his commitment to process-oriented soil fertility research in West Africa. *Soil Sci. Soc. Am. J*. 64: 346- 358.

Buerkert, A. and Schlecht, E. (2013). Agricultural innovations in small-scale farming systems of Sudano-Sahelian West Africa: Some prerequisites for success. *Secheresse 24: 332- 339.*

Buerkert, A., Bationo, A. and Piepho, H.-P. (2001). Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. Field Crops Research 72: 1-15.

Buerkert, A., and P. Hiernaux (1998) Nutrients in the West African Sudano-Sahelian zone: Losses, transfers and the role of external inputs. *Z. Pflanzen-ernahe. Bodenk 161: 365–383.*

Busani B. (2016). Innovative Use of Fertilizers revives hope for Africa's Green Revolution. Technical Report from *Africa Renewal, August-November 2016.3*

Caroline D.(2006). Imapcts de la Gestion de Fertilité sur les rendements en mil dans le Fakara, Niger. Mémoire de fin d'etudes de Bio-Ingenieur. Faculté d'ingénierie biologique, agronomique et environnementale. Universite Catholique de Louvain. 214.

Chen, J. (2006). The Combined Use of chemical and organic Fertilizers and /or Biofertilizer for Crop Growth and Soil Fertility. National Chung Hsing University, Taiwan. 11.

Chude O.V., Olayiwola S.O., Osho A.O, Daudu C.K.(2012). Fertilizer Use and Management Practices for Crops in Nigeria. *Ferderal Fertilizer Department. Federal Ministry of Agricultural and Rural Development*. *4th Edition. 230.*

CNABio. (2013). Norme Burkinabé en Agriculture Biologique. 42 p.

Comfort M.(2006). On-farm Yield and Water Use Response of Pearl Millet to different Management Practices in Niger. PhD Dissertation. Office of Graduate Studies of Texas A&M University.138.

Dabre E. (2008). Iinventaire et Importance des Insectes Ravageurs du Mil, *pennisetum glaucum* (leek) r. Br. En zone Sahélienne du Burkina Faso. Mémoire de fin d'études pour l'obtention de diplôme d'Ingénieur de développement Rural. Institut du Développement Rural. Université Polytechnique de Bobo-Dioulasso. 83p

Delassus M. (1964)**.** Les principales maladies du mil et du sorghot observées en Haute-volta en 1963. *Agronomie Tropicale 19(6), 489-498*

De Rouw, A., Rajot, J-L. 2004. Nutrient availability and pearl millet production in Sahelian farming systems based on manuring or fallowing. *Agriculture, Ecosystems and Environment, 104, 249-262*

FAO, (2012). La fertilisation localisée au semis des cultures ou microdose. *Fiche d'information. Niger.* 4.

FAO, (1992). Guide pour l'Interpretation des Analyses des Sols. 86.

Fatondji, D., Martius, C., Bielders, C., Vlek, P. L. G., Bationo, A. and Gerard, B. (2006). Effect of Planting Technique and Amendment Type on Pearl Millet Yield, Nutrient Uptake, and Water Use on Degraded Land in Niger. *Nutr. Cycl. Agroecosys. 76: 203-217.*

Fofana, B., Wopereis, M., Bationo, A., Breman, H. and Mando, A. (2008). Millet nutrient use efficiency as affected by natural soil fertility, mineral fertilizer use and rainfall in the West African Sahel. *Nutrient Cycling in Agroecosystems 81: 25-36.*

Gaston, S., Dahiratou, I. D., Moussa, B., & Dougbedji, F. (2016). Contribution of previous legumes to soil fertility and millet yields in West African Sahel. *African Journal of*

Agricultural Research, *11*(28), 2486–2498. https://doi.org/10.5897/AJAR2016.11156

Giller, K. E., Rowe, E., de Ridder, N. and van Keulen, H. (2006). Resource use dynamics, interactions in the tropics: Scaling up in space, time. *Agriculture Systems 88: 8-27*.

Giller K.E., Cadisch G., Ehaliotis C., Adams E., Sakala W.D., Mafongoya P.L. (1997). Building soil nitrogen capital in Africa. 152-191. In Buresh R.J., Sanchez P.A., Calhoun F. (eds.). Replenishing Soil Fertility in Africa. Soil Sci. Soc. Am. *Special Pub. Madison, WI. No.51*.

Girard C. (2001). Le cadre conceptuel des modèles de culture. thèse de doctorat. INRA 84 140 Avignon.

Giroux M. et Tran T.S., (1994). Etude des facteurs affectant l'évolution des teneurs en Pet K des sols agricoles. *Agrosol 7 (2) : 23-30.*

Guo, S., Wu, J., & Coleman, K. (2012). Soil organic carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-term nitrogen fertilizer applications, 321–332. *https://doi.org/10.1007/s11104-011-1034-1*

Han, X., Cheng, Z., & Meng, H. (2015). Soil Properties , Nutrient Dynamics , and Soil Enzyme Activities Associated with Garlic Stalk Decomposition under Various Conditions Soil Properties , Nutrient Dynamics , and Soil Enzyme Activities Associated with Garlic Stalk Decomposition under Various Conditions, (August). https://doi.org/10.1371/journal.pone.0050868

Hanspeter Liniger, Rima Mekdaschi Studer, Christine Hauert, M. G. (2011). Sustainable Land Management in Practice. *FAO*, 13.

Hayashi, K., Abdoulaye, T., Gerard, B. and Bationo, A. (2008). Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger, West Africa. *Nutrient Cycling in Agroecosystems 80: 257-265*

Henao, J., & Baanate, C. (2006). Agricultural production and soil nutrient mining in Africa: Implication for resource conservation and policy development. *Agricultural Roduction and Soil Nutrient Mining in Africa*, (March 2006), 15. Retrieved from www.ifdc.org

Herrmann, L., Jahn, R. and Stahr, K. (1996). Identification and quantification of dust additions in perisaharan soils. In The Impact of Desert Dust Across the Mediterranean, *173-182: Springer, The Netherlands.*

Houba, V., Van der Lee, J., Novozamsky, I., (1995). Soil Analysis Procedures; Other Procedures (Soil And Plant Analysis, Part 5B). Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, Wageningen, *The Netherlands, pp. 217*

Ibrahim, A., Abaidoo, R. C., Fatondji, D., & Opoku, A. (2015). Integrated use of fertilizer micro-dosing and Acacia tumida mulching increases millet yield and water use efficiency in Sahelian semi-arid environment. *Nutrient Cycling in Agroecosystems*, *103*(3), 375–388. https://doi.org/10.1007/s10705-015-9752-z

Ibrahim, A., Abaidoo, R. C., Fatondji, D., Opoku, A., Ibrahim, A., Abaidoo, R. C., … Opoku, A. (2016). Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system : A success with a shadow. *Soil and Plant Nutrition*, *768*(June), 13.

https://doi.org/10.1080/00380768.2016.1194169

Ibrahim, A., Clement, R., Fatondji, D., & Opoku, A. (2015). Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. *Field Crops Research*, *180*, 29–36. https://doi.org/10.1016/j.fcr.2015.04.022

Ibrahim, A., & Pasternak, D. (2014). Impact of depth of placement of mineral fertilizer micro-dosing on growth , yield and partial nutrient balance in pearl millet cropping system in the Sahel, (2003). https://doi.org/10.1017/S0021859614001075

Ibrahim, A., Pasternak, D., & Fatondji, D. (2015). Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel. *Journal of Agricultural Science, 153*(8), 1412–1421. https://doi.org/10.1017/S0021859614001075

Ibrahim A., Robert C.A, D., & F., O. A. (2016). Determinants of Fertilizer Microdosing-Induced Yield Increment of Pearl Millet on an Acid Sandy Soil. *Experimental Agriculture*, *52*(4), 562–578. https://doi.org/10.1017/S0014479715000241

ICRISAT Database(2017): Overview, Botany, Facts and Figures, Varietal Releases, Publications of Pearl millet.Retrieved from http://exploreit.icrisat.org/profile/Pearl%20Millet/178 on 12/12/2017.

ICRISAT. (2009). Fertilizer Microdosing: Boosting Production in Unproductive Lands. *Icrisat*, 4. Retrieved from www.icrisat.org/fertilizer microdosing.

IFA. (2009). Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainabily. *1st Edition, Paris, France.30.*

IFV. (2010). Fertilisation de la Vigne : La Réglementation (Fiche technique). Institut Français de la Vigne et du Vin. 7.

IPCC (2007). Fourth Assessment Report; *Cambridge University Press.* London. Intergovernmental Panel on Climate Change.

JIRCAS(2012). Une Utilisation efficace de la technique de micro dose d'engrais. *Manuel technique.* 32.

Johannes K. (2015). Adverse Impacts of mineral Fertilizers in Tropical Agriculture. *Henri Boll Stiftung. 2nd Edition, WWF Germany.60*.

Kapkiyai, J. J., Karanja, N. K., Qureshi, J. N., Smithson, P. C., & Woomer, P. L. (1999). Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management, *31*.

Keddal, H., N‟dri, Y. (2007). Impacts de l‟intensification agricole sur la qualité des eaux de surface et des eaux souterraines. *HTE 138, 17.*

Kelly N., Peter M., Ranjith U., S. J. and S. B. (2013). Global Achievements in Sustainable Land Management. *International Soil and Water Conservation Research, Vol.1 No.1,* 1–10. https://doi.org/10.1016/S2095-6339(15)30044-7

Krall S., Youm M. and Kogo A. (1995). Panicle insect pest damage and yield loss in pearl millet. *In* Panicle insect pests of sorghum and pearl millet: proceedings of an International Consultative Workshop, 4-7 Oct 1993, ICRISAT Sahelian Center, Niamey, Niger (Nwanze, K.F., and Youm. O., eds.). Patancheru 502 324, Andhra Pradesh, India: *International Crops Research Institute for the Semi-Arid Tropics. pp 135-145.*

Kretzschmar, R., Hafner, H., Bationo, A. and Marschner, H. (1991). Long-and short-term effects of crop residues on aluminum toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. *Plant and Soil 136: 215-223.*

Lawes Agricultural Trust (2007). Genstat. Lawes Agricultural Trust (Rothamsted Experimental Station), Rothamsted, UK.

Levallois, P., Phaneuf, D. (1992). Les risques associés à la contamination de l"eau potable par les nitrates. *Réseau de la santé publique du Québec Vol 3, 13.*

Maimouna. (2010). La simulation des composantes du rendement du mil sous la fertilisation par micro dose en utilisant le modèle DSSAT. Mémoire de fin d'études En vue de l'obtention du diplôme d'Ingénieur d'Etat en Sciences Agronomiques. *Université Ibn Khaldoun de Tiaret Faculté des Sciences Agronomiques et Veterinaires.* 62

Maiti, R. K., Bidinger F. R. (1981). Growth and development of the pearl millet plant. *ICRISAT research bulletin No 6*

Manu, A., Bationo, A. and Geiger, S. (1991). Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. Soil Science 152: 315-320.

Marchais (1993). Evaluation morphologique de cultivars de mil (P. glaucum (L.) R.Br.) collectés en Tunisie et en Afrique de l'Ouest, page 35-40.

Matlon P. (1983)**.** The technical potential for increased food production in the west African Semi-arid Tropics. Communication presentée à la « conference on Accelerated Agricultural Growth in Sub-saharian Africa ». 29 Août – 1 Septembre 1983, *Victoria Falls, Zimbabwe*.

Mbaye, D. F. (1993). Contraintes phytosanitaires du mil dans le Sahel: Etat des connaissances et perspectives. http://www.bondy.ird.fr/pleins_textes/pleins_textes_6/colloques2/38960.pdf

M'boye N. and Ruparao G., (1987). Les insectes ravageurs du mil en Afrique de l'Ouest et les moyens de lutte, in ICRISAT 1987. Proceedings of the International Pearl millet Workshop, 7-11 april 1986, ICRISAT center, India. Patancheru, A.P. 502324, India : ICRISAT.

Mc Intire J., (1982), Annual report of the ICRISAT Economics Program. Niamey- Niger : ICRISAT (Diffusion limitée).

Michels, K. and Bielders, C. L. (2006). Pearl millet growth on an erosion-affected soil in the Sahel. *Experimental Agriculture 42: 1-17.*

Mkhabelaa M. S., Warman P. R. (2005). The influence of municipal solid waste compost on yield, soil phosphorus availability and uptake by two vegetable crops grown in a Pugwash sandy loam soil in Nova Scotia. *Agr. Ecosys. Environ. 106: 57- 67.*

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. and Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature 490: 254-257.*

Nakamura, S., Hayashi, K., Omae, H., Ramadjita, T., Dougbedji, F., Shinjo, H., … Tobita, S. (2010). Validation of soil organic carbon dynamics model in the semi-arid tropics in Niger, West Africa. *Nutrient Cycling in Agroecosystems*, *89*(3), 375–385. https://doi.org/10.1007/s10705-010-9402-4

N'doye M. (1984), Etat de la contrainte phytosanitaire sur la culture du mil dans le sahel : Séminaire international Projet CILSS de lutte intégrée, Niamey, Niger, 6-13 décembre

1984.

N'Gone A. (2014). Etude sur l'Uttilisation des Enfrais biologiques dans dans l'Agriculture au Sud-Benin: Cas du Produit Agro Bio. Mémoire de fin d'etudes pour l'obtention de Mastere en Ingenierie de l'Eau et environment. *2iE. Burkina Faso. 97.*

Nouhou K.(2017). Hydrological Modelling of Zaï planting Pit for Rainwater Harvesting in Agroforestry Schemes for Climate Change Adaptation in the Sudano-sahelian Zone of Niger. PhD Thesis on Climate Change and Land Use, Kwame N'Krumah University of Science and Technology, Kumasi,Ghana.152.

Okebalama Chinyere. (2014). *Impact of Targeted Nitrogen and Phosphorus Microd-dosing on Maize and Cowpea Yields under Two Cropping Systems*. Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

Omar N. and Botourou O. (1987), Amelioration variétale du mil en Afrique de l'Ouest, in ICRISSAT 1987. Proceeding of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT center, India Patancheru, *AP. 502324*, India: ICRISAT

Pradat A. (1962). Le problème Quelea quelea (mange mil). *Agronomie Tropicale 18(1) : 137-* 142

Rabi, H. M. L. (2013). Effet de la fertilisation par microdose sur la productivité de des teneurs et les bilans partiels des nutriments. Memoire de fin d'études en vue de l'obtention du diplo,e de Master 2 en Gestion de Fertilité des Sols. *Universite Polytechnique de Bobo-Dioulasso.64.*

Rachie.K. and Majmudar.J. (1980)**.** Pearl Millet, University Park, Pennsylvania, USA : *The Pennsylvania State University Press. 307 pp*

Rebafka, F. P., Hebel, A., Bationo, A., Stahr, K. and Marschner, H. (1994). Short- and long-term effects of crop residues and of phosphorus fertilization on pearl millet yield on an acid sandy soil in Niger, West Africa. *Field Crops Research 36: 113-124*

Renard C and Kumar K.A. (2001), in Romain H. Raemaekers (2001), Agriculture en Afrique tropicale, *DGCI, B-1000 Bruxelles, Belgique, pp 70-84.*

Shapiro, B. I., Sanders, J. H. (1998). Fertlizer Use in Semiarid West Africa: Profitability and Supporting Policy. *Agricultural Systems, 56 (4), 467-482.*

Selvaraj C. (1980). Millet diseases and their control, Nigeria. Samaru Conference paper no 25. Samaru, Zaria, Nigeria : *Institute for Agricultural Research.*

Spencer D. and M. Sivakumar. (1987). Pearl Millet in African Agriculture, in ICRISAT.

Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, *A.P.502 324,* India: ICRISAT

Scheuring J. (1980)**.** ICRISAT millet improvement in CILSS cauntries of west Africa. Communication présentée à la réunion de CILSS sur l'amélioration des cultures vivrières, 8-11 decembre 1980.

Siband P. (1983), Essai d'analyse du fonctionnement du mil Pennisetum typhoïdes en zone sahelienne. *Agronomie tropicale 38(1) : 27-36*

Sivakumar, M. (1989). Agroclimatic aspects of rainfed agriculture in the Sudano-Sahelian zone. Smit, B., Burton, I., Klein, R. J., and Wandel, J. (2000). An anatomy of adaptation to climate change and variability. *Climatic change 45, 223-251.*

Sommer R, Bossio D, Desta L, Dimes J, Kihara J, Koala S, Mango N, Rodriguez D, Thierfelder C, Winowiecki L. (2013). Proftable and sustainable nutrient management systems for East and Southern African smallholder farming systems: challenges and opportunities: a synthesis of the Eastern and Southern Africa situation in terms of past experiences, present and future opportunities in promoting nutrients use in Africa. Cali (Colombia): CIAT. The University of Queensland. QAAFI. CIMMYT

Stoop W. A., Pattanaya K.C.M., Matlon P. J., et Root W.R. (1982), A strategy to raise the productivity of subsistance farming systems in the west African semi-arid tropics. Pages 519-526 in Sorghum in the eighties : Proceeding of the International Symposium 2-7 novembre 1981, ICRISAT center Inde. Vol 2. Patancheru, *A.P. 502 324*, Inde : ICRISAT.

Suzuki, K., Matsunaga, R., Hayashi, K., & Matsumoto, N. (2017). Agriculture , Ecosystems and Environment Effects of long-term application of mineral and organic fertilizers on dynamics of nitrogen pools in the sandy soil of the Sahel region , Niger. *"Agriculture, Ecosystems and Environment," 242*, 76–88. https://doi.org/10.1016/j.agee.2017.03.004

Tabo, R., Bationo, A., Amadou, B., Marchal, D., Lompo, F., Gandah, M., Hassane, O., Diallo, M. K., Ndjeunga, J., Fatondji, D., Gerard, B., Sogodogo, D., Taonda, J. B. S., Sako, K., Boubacar, S., Abdou, A. and Koala, S. (2011).Fertilizer Microdosing and "Warrantage" or Inventory Credit System to Improve Food Security and Farmers' Income in West Africa. In Innovations as Key to the Green Revolution in Africa, 113-121 (Eds A. Bationo, B. Waswa, J. M. Okeyo, F. Maina and J. M. Kihara). *Springer, The Netherlands.*

Tabo R, Bationo A, Diallo Maimouna K, H. O. and K. S. (2007). Fertilizer micro dosing for the prosperity of the small scale farmers in the Sahel. *: International Crops Research Institute for the Semi-Arid Tropics, No 23*, 28.

Tampa T. (1983). Etude du problème des chibras et de l'Evaluation des pertes de rendement liées au chibra: Elaboration d'une méthodologie d'épuration des cultivars locaux. Mémoire de fin d'études. Institut polytechnique rural, Katibougou, Mali 50.

Tan, Z. X., & Lal, R, K. D. W. (2005). Global Soil Nutrient Depletion and Yield Reduction. *Journal of Sustainable Agriculture, USA, 26*(1), 123–146.

Terrafrica. (2016). The Role of Sustainable Land Management for Climate Change Adaptation and Mitigation in Sub-Saharan Africa. *Terrafrica*, 12.

Traore S., Bagayoko M., Coulibaly B. and Coulibaly A. (2003). Amélioration de la gestion de la fertilité des sols et celle des cultures dans les zones Sahéliennes de l'Afrique de l'Ouest : une condition sine qua none pour l'augmentation de la productivité et de la durabilité des systèmes de cultures à base de mil. 25 p.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N. and Mahposa, P. (2011).Micro-dosing as a pathway to Africa's 159 Green Revolution: evidence from broad-scale on-farm trials. In Innovations as Key to the Green Revolution in Africa, 1101-1113: *Springer, The Netherlands*

van Reeuwijk, L.P., (1993). Procedures for soil analysis. Technical paper No 9, Fourth edition edited by the *International Soil Reference and Information Center (ISRIC).*

Voortman, R. L., Brouwer, J. and Albersen, P. J. (2004). Characterization of spatial soil variability and its effect on millet yield on Sudano-Sahelian coversands in SW Niger. *Geoderma 121: 65-82*

Walkley, A., Black, I.A., (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci. 37, 29–38.*

West, L. T., Wilding, L. P., Landeck, J. K. and Calhoun, F. G. (1984). Soil survey of the ICRISAT Sahelian Center, Niger, West Africa.

Williams R and Andrews D. (1983). Breeding for desease and pest resistance in pearl millet *FAO Plant Protection Bulletin 31(4) : 136-158.*

Wolf, J., Ittersum, M. K. Van, Bussel, L. G. J. Van, Wolf, J., Grassini, P., Wart, J. Van, & Guilpart, N. (2016). Can sub-Saharan Africa feed itself ? Can sub-Saharan Africa feed itself ?, (December). *https://doi.org/10.1073/pnas.1610359113*

Wopereis, M., Defoer, T., Idinoba, P., Diack, S., Dugue, M.-J. (2008). Curriculum d‟Apprentissage participatif et Recherche Action (APRA) pour la Gestion intégrée de la Culture de Riz de Bas-Fonds (GIR) en Afrique subsaharienne *(Manuel technique). Centre du riz pour l‟Afrique (ADRAO), Cotonou, Bénin. 125*

Yara.(2017). Fertilizer Industry Handbook. Book retrieved on 12th August 2017 from the website: http://www.yara.com/investor_relations/reports_presentations/index.aspx

Zodomé, G. (2012). Evaluation de la performance du riz Oryzae sativa à différentes doses d‟engrais chimiques et organiques sur sol sablonneux au centre du Bénin (Rapport de fin de stage, Licence professionnel). Bénin. 42

Zougmoré, R., Jalloh, A., & Tioro, A. (2014). Climate-smart soil and water management options in semi arid West Africa: A review of evidence and analysis of stone bunds and zai techniques. *Agriculture & Food Security*, *3*(16), 1–8.

APPENDICES

APPENDIX A: ANOVA of the different variable of change in soil nutrients of the experiment

1. Variate: pH_H2O

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	0.05102	0.02551	1.14	
Rep.*Units* stratum					
Fertilisant	1	0.07053	0.07053	3.15	0.126
Sampling_position	1	0.00013	0.00013	0.01	0.941
Fertilisant.Sampling_position	1	0.00213	0.00213	0.10	0.768
Residual	6	0.13425	0.02237		
Total	11	0.25807			

2. **Variate: Total_N_(mg_kg)**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	471.3	235.7	0.60	
Rep.*Units* stratum					
Fertilisant	1	332.7	332.7	0.84	0.394
Sampling_position	1	792.4	792.4	2.01	0.206
Fertilisant.Sampling_position					
	1	21.1	21.1	0.05	0.825
Residual	6	2368.5	394.7		

Total 11 3986.1

3. **Variate: P_Bray1_mg_kg**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	2.3338	1.1669	1.92	
Rep.*Units* stratum					
Fertilisant	1	11.5248	11.5248	18.92	0.005

Sampling_position	1	5.5216	5.5216	9.07	0.024
Fertilisant.Sampling_position					
	1	7.2696	7.2696	11.94	0.014
Residual	6	3.6543	0.6090		
Total	11	30.3042			

4. Variate: K_mg_kg

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	122.86	61.43	1.18	
Rep.*Units* stratum					
Fertilisant	1	57.38	57.38	1.10	0.335
Sampling_position	1	1610.08	1610.08	30.82	0.001
Fertilisant.Sampling_position					
	1	95.77	95.77	1.83	0.225
Residual	6	313.48	52.25		

Total 11 2199.57

5. **Variate: %OC**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	0.0009500	0.0004750	0.74	
Rep.*Units* stratum					
Fertilisant	1	0.0008333	0.0008333	1.30	0.298
Sampling_position	1	0.0005333	0.0005333	0.83	0.397
Fertilisant.Sampling_position					
	1	0.0000333	0.0000333	0.05	0.827
Residual	6	0.0038500	0.0006417		
Total	11	0.0062000			

APPENDIX B: ANOVA of different crop yield components

1. **Variate: Rendement_tige_kg_ha**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	7796896	3898448	3.26	
Rep.Plot stratum					
Fert_l	3	20558885	6852962	5.73	0.034
Residual	6	7177859	1196310	2.16	
Rep.Plot.Year stratum					

Year	8	2.04E+08	25440790	45.94	<.001
Year.Fert_l	24	12686481	528603	0.95	0.534
Residual	64	35439111	553736		
Total	107	2.87E+08			

2. **Variate: Rendement_grain_kg_ha**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	416221	208111	1.74	
Rep.Plot stratum					
Fert_l	3	1271222	423741	3.54	0.088
Residual	6	718934	119822	3.47	
Rep.Plot.Year stratum					
Year	8	9237427	1154678	33.4	<.001
Year.Fert_l	24	938535	39106	1.13	0.339
Residual	64	2212739	34574		
Total	107	14795078			

3. **Variate: Biomass_totale**

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	14946568	7473284	3.23	

Rep.Plot stratum					
Fert_l	3	39042437	13014146	5.63	0.035
Residual	6	13876128	2312688	2.75	
Rep.Plot.Year stratum					
Year	8	3.06E+08	38295324	45.54	<.001
Year.Fert_l	24	19306018	804417	0.96	0.531
Residual	64	53814572	840853		
Total	107	4.47E+08			

APPENDIX C: Showing the calculation of change in different soil nutrients of the experimental field

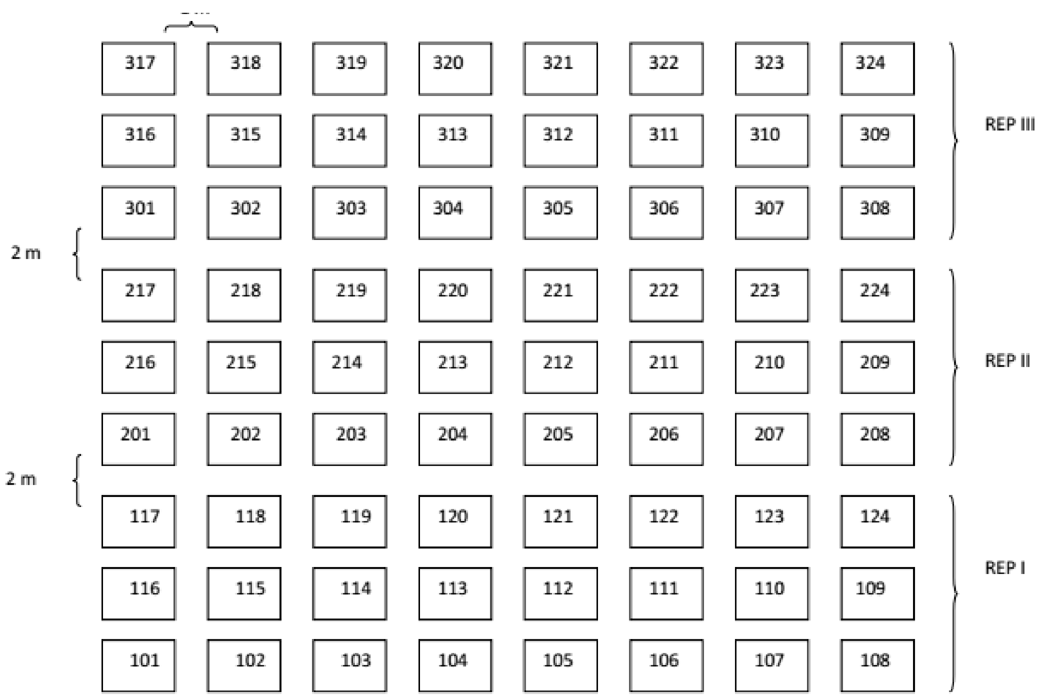
Replication	Fertilizer treatment	Sampling position	Soil depth(cm)	pH-H_2O	P Bray-1(mg/kg)	Total N(mg/kg)	%C	K^+(mg/kg)	% pH-H_2O change	% P Bray-1 change	% Total N change	% K^+change	% C change
1	Control	Between hill	0-40	-0.18	-0.22	-26.43	-0.09	-9.08	-3.47	-8.06	-14.71	-14.91	-39.72
1	Control	planting hill	0-40	-0.55	-0.28	-49.82	-0.10	-9.45	-10.67	-10.21	-27.73	-15.33	-43.18
1	NPK(6g)	Between hill	0-40	-0.58	0.22	-32.65	-0.07	-24.07	-11.39	8.07	-18.17	-39.53	-31.02
1	NPK(6g)	Planting hill	0-40	-0.62	2.25	-2.80	-0.03	12.89	-12.03	82.81	--1.56	21.17	-14.28
2	Control	Between hill	0-40	-0.58	0.13	-43.85	-0.07	-23.32	-11.39	4.85	-24.40	-38.31	-33.74
2	Control	planting hill	0-40	-0.27	-0.23	-15.24	-0.06	4.93	-5.16	-8.60	-8.48	8.10	-26.33
2	NPK(6g)	Between hill	0-40	-0.52	0.93	-7.78	-0.04	-17.93	-10.15	34.45	-4.33	-29.44	-16.77

2	NPK(6g)	Planting hill	0-40	-0.45	5.25	6.65	-0.04	11.03	-8.79	19.53	3.70	18.11	-19.90
3	Control	Between hill	0-40	-0.23	0.18	-37.63	-0.07	-14.34	-4.51	6.46	-20.94	-23.55	-29.93
3	Control	planting hill	0-40	-0.27	0.00	-2.06	-0.02	10.33	-5.35	0.01	-1.14	16.96	-10.73
3	NPK(6g)	Between hill	0-40	-0.43	0.15	-43.85	-0.06	-8.57	-8.47	5.38	-24.40	-14.07	-28.09
3	NPK(6g)	Planting hill	0-40	-0.40	2.54	-31.41	-0.07	11.96	-7.88	93.56	-17.48	19.64	-31.38

APPENDIX D: Experimental design of the long-term field experiment

Experimental Design: RCBD
Repetition: 3
Treatments: 24
Elementary plot: 6m x 6m
Useful plot: 25m^2

Factors:
Varieties: 2 level (Local Sadore and HKP)
Mineral fertilizer: 4level (**E1**: Control, **E2**: 2g DAP+ 1g Urea, **E3**: 3g NPK, **E4**: 6g NPK)
Density: 3 level: **D1**: 5000 hills/ha, spacing=1.5m x 1m
D2: 10000 hill/ha, spacing= 1.mx 1m
D3: 15000 hills/ha, spacing= 0.8mx 0.8m



APPENDIX E: Soil survey during fieldwork


Champs : BB, ISC
Essai : Microdose + R
Sustainability sampling
éch. de sols Composite
Plot : 124
Densité semis : 1m x 1m
Variété : Sadoré local
Fertilisant : NPK, 3 grs
Champs : BB, ISC
Essai : Microdose + R
Sustainability sampling
éch. de sols Composite
Plot : 124
Densité semis : 1m x 1m
Variété : Sadoré local
Fertilisant : NPK, 3 grs
Prof : 0 - 10 cm

APPENDIX F: Conference paper presented at 2017 conference of Environmental Management Association of Niageria(EMAN). Port Harcourt 5-8 December 2017

Soil Nutrient Dynamics under Long-term Application of Mineral Fertilizer Micro-dosing on Sandy Soils in the Sahel region of Niger Republic

[1*] Sani Issa M. S., [2] Ezenwa M.I.S, [3]Fatondji D., [1] Okhimamhe A.A and [3] ALI I.

[1] *Master Research Program on Climate Change and Adapted Land Use, WASCAL, Federal University of Technology, Gidan Kwano Campus*
PMP 65, Minna, Niger State, Nigeria
E-mail: mahamansanoussi@gmail.com
[*]Corresponding author

[2] *Department of Soil Science and Land Management, Federal University of Technology, Gidan Kwano Campus,*
PMP 65, Minna, Niger State, Nigeria

[3] *International Crops Research Institute for the Semi-Arid Tropics, Sahelian Center Sadore*
P.O. BOX 12404, Niamey, Niger

ABSTRACT

Fertilizer micro-dosing technique is known for its benefits to provide higher nutrient uptake and higher crop yields. However, the question is whether the application of this technology would not lead to soil nutrients mining in the long-term following this yield increase with corresponding nutrient uptake. A study was set up at ICRISAT research station at Sadore in Niger, which aims at evaluating the sustainability of the technology in the long-term with emphasis on soil nutrients dynamics. The study started since 2008 and was laid out in a Randomized complete block design that involved two pearl millet varieties, three planting densities, and four nutrients management options. For the purpose of the present study, we have used a sub-set of the treatments from this long term experiment. The nutrient management factor, which includes 4 levels was considered. Soil survey was carried out as in each of the corresponding plot, soil samples were collected both between and on the planting hills. In total, 36 soil samples were collected and analyzed. The findings of the study showed that the change in soil nutrient was markedly different on the planting hills and that from between hill spaces. This change in soil pH-H_2O values on the planting hill was -7.06% for the control plots and -9.57% for the plots applied with NPK. Hence, this negative change resulted in possible acidification of the experimental site. The total nitrogen content has dropped in both the control plots and the plots that received NPK as microdose. The amplitude of drop has lowered with the application of

NPK microdosing on the planting hills with respectively -5.11% and -12.45% in the control plots and the plots receiving NPK. Positive change in available P was significantly observed ($P \leq 0.05\%$) in soil between hill with 1.08% in the control plots and 15.97% in the plots amended with NPK. While on the planting hills, the change was higher in plots applied with NPK compared to the control plots with respectively 88.19% and -6.27%. Therefore, to reverse the soil nutrients mining effect of fertilizer micro-dosing technology in Sahelian millet cropping system, crop residues recycling must be considered.

Key words: Fertilizer micro-dosing, sustainability, nutrient mining, long-term, Sahel.

1. INTRODUCTION

In Sahel, one of the most striking constraints that impedes crop productivity is low soil fertility (Batiano *et al.*, 2012; Bielders, 2015). Soil nutrient depletion is a major concern in many African countries mostly in Sahelian region where low-input small scale farming systems are predominant (Ibrahim *et al*., 2016). Reports from Sommer *et al.* (2013) showed that soil nutrient mining is widespread, with a combined average depletion rate of N, phosphorus (P) and potassium (K) of 54 kg per hectare per year in sub-Saharan Africa. Earlier findings from the study conducted in the long term experiment at Sadore Sahelian Centre of International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) have indicated that N and P nutrients significantly affect the grain yield and total dry matter of pearl millet (Akponikpé; 2014 and Suzuki *et al*.,2016). The technology of fertilizer microdosing application, which consists of placing small amounts of fertilizer at the hill of plants (ICRISAT, 2009), is widely recognized as a strategy of nutrient management in integrated manner so as to sustain agronomic productivity (Ibrahim *et al.*, 2015, Ibrahim *et al*., 2014, Rabi, 2013, Maimouna, 2010 and Tabo *et al.*, 2006). Recent reports from (Suzuki et *al.*, 2017, Akponikpè et *al.*, 2014 and Ibrahim *et al.*, 2015) confirmed that the use of mineral fertilizer in combination with manure resulted in high crop yields in Sahel. However, regardless of the increase in crop yields induced by mineral fertilizer micro-dosing technology, (Camara *et al.*, 2013 and Ibrahim *et al*., 2016) pointed out the fact that such technology leads to an increase of risk of high nutrient export in low-input millet based cropping system and consequently decreased soil fertility. On the other hand, Ibrahim *et al.*,(2015), showed that an increase of fertilizer application depth ranging from 5-10 cm gave a significant increases in terms of the root length density while higher depth of the application of fertilizer has given an increase of high yields. Hence, the preservation and maintenance of fertility necessitate the investigation of nutrient element regime of the soil, which represent the life media for microbial activities as well as crop. This necessitates a regular monitoring of changes in soil fertility that occurs in the soil (Batiano *et al.*,2011). Actually, little studies have been carried out in order to determine the sustainability of that technology. It appears that crop roots are mainly concentrated where nutrients are located but nevertheless, lateral root development is also observed. Hence between hill spaces that in the context of micro-dosing do not receive input, is expected to provide nutrients to crops. Therefore, to have a better idea of the sustainability of the technology, the best approach would be to study nutrient dynamics at hill level.

For the current study, the general hypothesis drawn is that as result of hill application of the mineral fertilizer microdosing, soil nutrients dynamics on the planting hill will be better and different from that of the soil between the planting hills. The objective of the current study was therefore, to evaluate nutrients dynamics from the long term application of mineral fertilizer microdosing and thus determining the level of contribution of planting hill focused and between hills focused nutrients dynamics to soil fertility sustainability of the technology.

2. MATERIAL AND METHODS

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 at sea level). The climatic conditions are characterized by a long and hot dry season (November to May) followed by a very short rainy season between June and September. A highly variable rainfall with an annual average of 550mm and average temperature is 29°C (ICRISAT database 1984-2016). The field trial is a long-term experiment of a combination pearl millet and mineral fertilizer microdosing started since 2008 and crop residues are left in the field every year. The soil type in Sadore is classified as a sandy Arenosol (West *et al.* 1984). The field experiment had a sandy soil. The SOC (soil organic Carbon) content and extractable P (P-Bray) were all very low with 0.22% and 2.7 mg kg^{-1} respectively. The total Nitrogen (N) content was low with 179 mg kg^{-1} and soil pH (H_2O) was strongly acidic(Table1).

2.2. Treatments and Experimental Design set-up

The experiment was arranged in a randomized complete block design (RCBD) with three replications. The treatments combination was the factorial combination of (a) four different nutrient management options (control, 3g of NPK, 6g of NPK and 2g of DAP+ Urea at elongation stem period), (b) two genotypes of pearl millet (Sadoré local and HKP variety), (c) three planting densities (Density 1= 5000 hills/ ha); spacing = 1.5mx1m; Density2 = 10 000 hills/ ha); spacing = 1mx1m and Density3 = 15 000 hills/ ha); spacing = 0.8m x0.8 m). Plot dimensions were 6m x 6m and the gross dimension of the experiment was 64 m x 55 m = 3569 m^2. Then, between row spacing was 1m whereas between replication spacing was 2m and the useful plot size is 25 m2.

For the present study, we have subsetted from the long-term experiment our experiment. Only one factor was considered and the treatments were also laid out in an RCBD. The factor is mineral fertilizer with two nutrient management options (0 input (control), 6g. $hill^{-1}$ of NPK (15-15-15). The treatment combination consisted of (a) local variety of pearl millet (local Sadoré), (b) density (1 x 1 m) and (c) one nutrient management options of inorganic fertilizer.

2.3. Soil sampling and analysis

Regarding this study, we have benefited from data initially collected in the experiment being conducted since 2008 where crop and soil data are collected on yearly basis. Before trial layout in 2008, initial soil samples were collected from each replication. After every two years, samples collection was carried out in each individual plot between the planting. In the present study conducted in June 2017, in addition to 4 composite samples collected between the planting hills, 4 planting hills were also selected randomly on which the same core of samples were collected so as to achieve the objectives of the current study. For the samples collection, a graduated aluminum tube was adapted and used as soil sampling auger. In total 36 soil samples were collected and three cores samples were considered: 0 – 10 cm; 10 – 20 cm and 20 – 40 cm**.**

Each sample was analysed for pH-H2O (soil/water ratio of 1:2.5), soil organic carbon was determined with the method described by Walkley and Black (1934), total N by Kjeldahl method (Houba et al., 1995), exchangeable K^+ and extractable phosphorus were determined respectively by using the extraction method described by van Reeuwijk (1993) and the Bray 1 method (van Reeuwijk, 1993).

2.4. Procedures for statistical analysis

After the laboratory analyses of the samples, data were processed using Excel. The change in soil nutrients was calculated as follows:

$$\text{Change in N, P, K} = \frac{(\text{ASNC} - \text{ISNC})}{\text{ISNC}} * 100$$

Where ASNC is the actual soil nutrients content of the experimental field and ISNC is the initial soil nutrients content of the experimental field.

Thereafter, statistical analysis was done with GENSTAT v.9.2 (Lawes Agricultural Trust, 2007) where analysis of variance was hence performed by using a general treatment structure (in Randomize Blocks). Differences between treatments were considered at error probabilities ≤ 0.05.

3. RESULTS AND DISCUSSION

3.1. Soil properties of the long term experimental field

Table 1 and 2 show the initial characteristics of the long term experiment site. Based on FAO guidelines (1992) for interpretation of soil analysis, it is concluded that the SOC content and extractable P (P-Bray 1) were all very low with 0.22% and 2.7 mg kg^{-1} respectively. The total Nitrogen (N) content was low with 179 mg kg^{-1} and soil pH (H_2O) was strongly acidic. The texture class was determined using textural triangle(FAO,1992).

Table 1: Initial chemical characteristics of the long term experiment site

Soil depth (cm)	pH-H_2O (1:2.5)	Org C (%)	Total-N (mg/kg)	Available P (mg/kg)	K+ (mg/kg)
0-10	5.1±0.03	0.33±0.004	280±13	3.7±0.3	107±40
10-20	5.2±0.08	0.19±0.01	153±5	2.3±0.1	43±6
20-40	5.1±0.06	0.14±0.005	105±3	2.1±0.2	33±5
Mean values	5.1±0.05	0.22±0.02	179±6.33	2.7±0.2	161±17

±Standard error.

Table 2: Particle size distribution

Soil depth (cm)	% sand(g.Kg^{-1})	% slit (g. Kg^{-1})	% clay(g.Kg^{-1})
0-10cm	94.6±0.2	2.4±0.1	3.0±0.2
Textural class		**Sandy**	

±Standard error.

3.2. Current soil nutrient measurements of the experiment site

Table 3 illustrates the actual soil nutrient content of the experiment site. It is observed that pH values have decreased compared to the initial values. On the plots applied with NPK as micro-dose, the soil pH the same (4.6) while the mean of pH before trial layout in 2008 was 5.1. This indicates that the soil is getting acidic despite the application of the micro-dosing mineral fertilizer. The trend is similar concerning the SOC which remains constant (0.2%) as average although crop residues are every year left in to the experiment site. It is concluded that this may be due to the production of biomass which export much nutrient instead of sequestering into the soil. Nevertheless, the dose of available P has increased over time with application of micro-dosing mineral fertilizer micro-dosing with respectively 3.1 mg. Kg^{-1} and 6.1 mg. Kg^{-1} for the between hills and the planting hills. It is observed an increase of available P at the planting hills compared to between hills. This could be due to the P accumulation of P into the soil over time.

Table 3: Current characteristics of chemical parameters of the experiment site

	Sampling position	pH-H2O	P Bray1 (mg/kg)	Total N (mg/kg)	%OC	K+(mg/kg)
Control	Between hill	4.7	2.7	141.6	0.1	45.3
Control	Under hill	4.8	2.5	157.3	0.2	62.8
NPK(6g.hill)	Between hill	4.6	3.1	151.6	0.2	44.0
NPK(6g/hill)	Under hill	4.6	6.1	170.5	0.2	72.8

3.3. Changes in soil nutrients content of the experimental field

3.3.1. Change in soil pH-H_2O of the experimental site

The change in soil pH-H_2O is presented in figure 1.

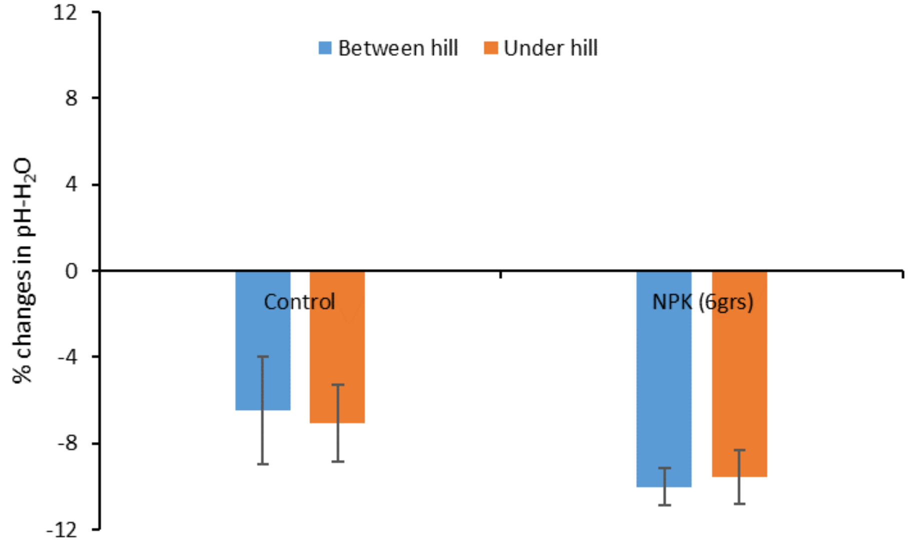


Figure 1: Change in the pH (H2O) values from 2008 to 2017of the experiment site as affected by treatments

Figure 1 shows that after 9 seasons of cropping, soil pH-H_2O decreased in both the control plot and that applied with 6g of NPK (15-15-15) as microdose. In the control plot as well as in the fertilized plots, the amplitude of the change in pH-H_2O was similar whether the sample was collected between the planting hills or on the hills. When compared with the control plots, soil acidity has increased significantly more on the planting hill than between the hill ($p \leq 0.05$). Change in soil pH was -7.06% for the control plot and -9.57% for the plots applied with NPK. The higher negative percentage of this change indicated that a possible acidification of the soil experiment occurred. These results confirm the findings obtained by Rabi (2013) that showed a variation of soil pH-H_2O value of about -0,45 after applying 1g of NPK on the planting hill of sesame farm in Kollo(Niger).

3.3.2. Changes in total nitrogen

Results concerning change in total N occurred in the experimental field are presented in figure 2.

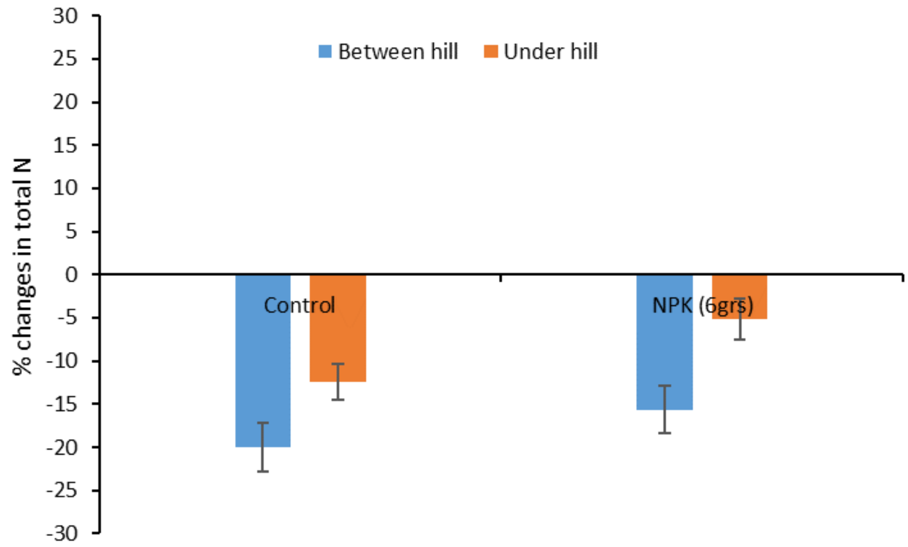


Figure 2: Change in total nitrogen content of the soil as affected by treatments

Soil total nitrogen content has dropped over the year of cropping in both the control plot and the plot receiving NPK as microdose. This negative change in total Nitrogen was more important with respect to between the hills than to the planting hills regardless of the treatment received. The amplitude of nitrogen content drop was lower in the plot applied with NPK than in the control plots. Application of 6g of NPK has lowered the amplitude of nitrogen content drop on the planting hill (-5.11%) compared to the control plot (-12.45%) indicating partial replenishment compared to the between hill space and the control. Therefore, micro-dosing option significantly ($p \leq 0.005\%$) affected Nitrogen content. The negative change might be due to the mobile character of N into the soil and to the soil nutrient export from biomass production of pearl millet. These results are in line with the work of (Buerkert, 1995 and Bandoum, 2005) where they showed that fertilizer micro-dosing caused nutrient export initially present in the soils. These results also agree the findings obtained by Ibrahim *et al*., (2016), they found that fertilizer micro-dosing with (2g DAP and 6g NPK) had a negative effect on both partial and full nutrient balance in pearl millet field. Added to that, the work of Rabi (2013) confirmed that total dry matter of sesame local variety seriously exported partial nutrient balance with about 21.9 g/kg N with application of NPK at hill. Therefore, it is concluded that fertilizer micro-dosing has led to a negative contribution with regard to partial and full soil nutrient balances instead of increasing such nutrient balances. However, Ibrahim *et al*., (2016) reported that a combined use of fertilizer micro-dosing along with manure had a positive partial nutrient balance. This indicates that pearl millet used significantly much more nutrients from the native soil nutrients. On the other hand, the highest percentage of change observed between hills may be due to the lateral root development of pearl millet that permit to the plant to look for nutrients far from the hill. This is a strategy of pearl millet adopted so as to benefit from nutrients where they are concentrated (Ibrahim *et al.* , 2015).With such nutrient mining character of fertilizer micro-dosing, cropping system could not be quite sustainable meaning that the technology cannot sustain the nutrient requirements of pearl millet over time.

3.3.3. Changes in extractable Phosphorus (P-Bray1)

Figure 3 presents the change in extractable phosphorus content of the experimental soil from 2008 to 2017.

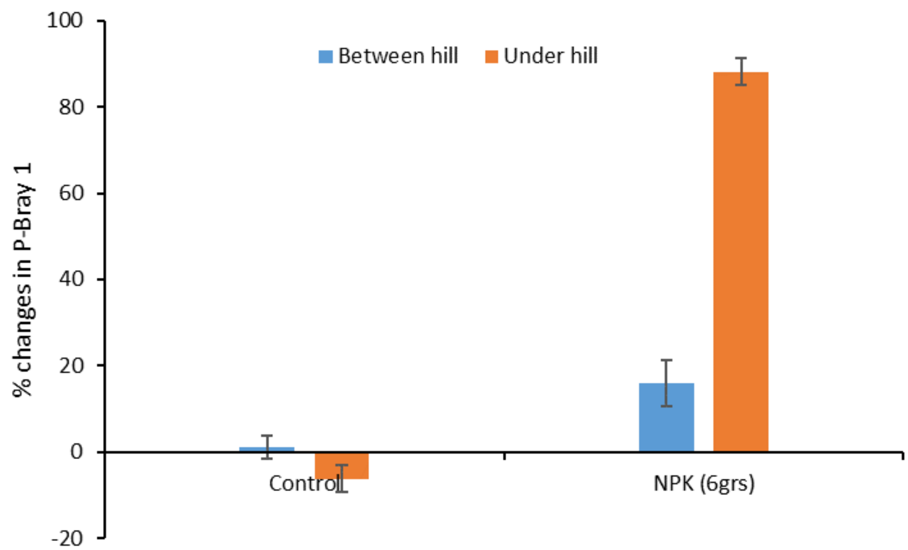


Figure 3: Change in extractable Phosphorus content of the experimental soil as affected by treatments.

Higher and positive change was observed in plots applied with NPK compared to the control particularly on the planting hills (88.19% vs -6.27%). In both the control and the fertilized plot, positive change was observed in available P in soil between the planting hills. This is an indication that even though P export through biomass production has occurred in both treatments, P accumulation has occurred in the plot applied with NPK. Presumably P mobilization from the soil pool have occurred that was more important on the planting hills. Research has shown that pH, Fe, Al and Ca concentration as well as soil texture and organic matter significantly affect P availability for the plant (Mkhabelaa and Warman, 2005). In acidic soils and particularly with sandy structure like the one of our experiment with up to 47% aluminium saturation (Fatondji *et al*., 2006), it is expected that P immobilization occurs at pH lower than 5. In the sampled plots, soil pH has dropped from 5 to 4.8(figure1).

4. CONCLUSION

The change in soil nutrients obtained in this study showed that fertilizer micro-dosing stimulates the export of soil nutrients that are initially into the soil which consequently encourages the soil impoverishment. Thus, fertilizer micro-dosing significantly affects soil nutrients in the long term. It is concluded that the trend of the change in soil pH-H_2O as well as in total nitrogen content were negative. However, only available Phosphorus has presented positive change. The change in soil nutrients dynamics is better on the planting hills than that from between hills space. Therefore, the study concluded that the hill placement character greatly influences soil nutrients dynamics in long-term application of micro-dosing. Hence, we concluded that the soil nutrients dynamics at planting hill were better and different from soil between hills due to the hill application character. Further research should be implemented in order to assess thoroughly the sustainability of that technology. Finally, for the technology to be as much as sustainable in the long-term, it is recommended to establish strategies which will sustainably improve and maintain soil fertility in Sahel zones and thus reduce its nutrient mining effect.

ACKNOWLEDGEMENTS

This research was funded by the German Federal Ministry of Education and Research (BMBF) through West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). We are also grateful to ICRISAT-Niamey for the facilities placed to our disposal. Especially, we are most thankful to ICRISAT staff Laouali Issaka and Moustapha Adamou for their technical assistance during our data collection.

STATEMENT OF NO-CONFLICT OF INTEREST

We the author of the paper declare that there are no conflict of interests regarding this publication.

REFERENCES

Akponikpè, P. B. I., Gérard, B., & Bielders, C. L. 2014. Soil water crop modeling for decision support in millet- based systems in the Sahel : A Challenge, *9*(7), 1700–1713. https://doi.org/10.5897/AJAR10.263

Bandoum Y. P., 2005. Effets de la fertilisation par micro dose sur la productivité du mil, les bilans des nutriments et de l'eau du sol au Niger. Mémoire de fin d'étude. Faculté d'Agronomie, Université Abdou Moumouni, pp. 1-57.

Bationo, A., Kihara, J., Adesina, A. 2012. Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Improving Soil Fertility Recommendations in Africa Using the Decision Support System for Agrotechnology Transfer (DSSAT*)*, (January 2012), 169–184. https://doi.org/10.1007/978-94-007-2960-5

Bationo, A. and Waswa, B. (2011).New challenges and opportunities for integrated soil fertility management in Africa. In Innovations as key to the green revolution in Africa, 3-17: Springer, The Netherland

Bielders, C. 2015. Microdose fertilisation : A Step on the Ladder towards Crop Intensification in the Sahel ? *Earth and Life Institute*, 1–11.

Buerkert A., 1995. Effects of Crops Residues, Phosphorus, and Spatial Soil Variability on Yield and Nutrient Uptake ofPearI Millet (Pennisetum glaueum (L.) R. Br.) in Southwest Niger. *PhD Thesis*.VerIag Ulrich E. Grauer, Stuttgart, pp. 1-272.

Camara B, Camara F, Berthe A, Oswald A 2013: Micro-dosing of fertilizer: A Technology for Farmers' Needs and Resources. Int. J. AgriScience, 3(5), 387–399

FAO, (1992). Guide pour l'Interpretation des Analyses des Sols. 86.

Fatondji, D., Martius, C., Bielders, C., Vlek, P. L. G., Bationo, A. and Gerard, B. 2006. Effect of Planting Technique and Amendment Type on Pearl Millet Yield, Nutrient Uptake, and Water Use on Degraded Land in Niger. Nutr. Cycl. Agroecosys. 76: 203-217.

Gaston, S., Dahiratou, I. D., Moussa, B., & Dougbedji, F. (2016). Contribution of previous Legumes to Soil Fertility and millet yields in West African Sahel. *African Journal of Agricultural Research*, *11*(28), 2486–2498. https://doi.org/10.5897/AJAR2016.11156

Houba, V., Van der Lee, J., Novozamsky, I., 1995. Soil Analysis Procedures; Other Procedures (Soil And Plant Analysis, Part 5B). Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, Wageningen, The Netherlands, pp. 217

Ibrahim, A., Abaidoo, R. C., Fatondji, D., Opoku, A., Ibrahim, A., Abaidoo, R. C., … Opoku, A. 2016. Soil Science and Plant Nutrition Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system : A success with a shadow. *Soil and Plant Nutrition*, *768*(June), 13. https://doi.org/10.1080/00380768.2016.1194169

Ibrahim, A., Clement, R., Fatondji, D., & Opoku, A. 2015. Field Crops Research Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. *Field Crops Research*, *180*, 29–36. https://doi.org/10.1016/j.fcr.2015.04.022

Ibrahim, A., & Pasternak, D. 2014. Impact of depth of placement of mineral fertilizer micro-dosing on growth , yield and partial nutrient balance in pearl millet cropping system in the Sahel. https://doi.org/10.1017/S0021859614001075

ICRISAT. 2009. Fertilizer Microdosing: Boosting Production in Unproductive Lands. *Icrisat*, pp 4. Retrieved from www.icrisat.org/fertilizer microdosing.

Maimouna. 2010. La simulation des composantes du rendement du mil sous la fertilisation par micro dose en utilisant le modèle DSSAT. Mémoire de fin d'études En vue de l'obtention du diplôme d'Ingénieur d'Etat en Sciences Agronomiques. Université Ibn Khaldoun de Tiaret Faculté des Sciences Agronomiques et Veterinaires, pp 62.

Mkhabelaa M. S., Warman P. R. 2005. The influence of municipal solid waste compost on yield, soil phosphorus availability and uptake by two vegetable crops grown in a Pugwash sandy loam soil in Nova Scotia. Agr. Ecosys. Environ. 106: 57- 67.

Rabi, H. M. L. 2013. Effet de la fertilisation par microdose sur la productivité de des teneurs et les bilans partiels des nutriments. Memoire de fin d'études en vue de l'obtention du diplo,e de Master 2 en Gestion de Fertilité des Sols. Universite Polytechnique de Bobo-Dioulasso pp. 1-64.

Sommer R, Bossio D, Desta L, Dimes J, Kihara J, Koala S, Mango N, Rodriguez D, Thierfelder C, Winowiecki L. 2013. Proftable and sustainable nutrient management systems for East and Southern African smallholder farming systems: challenges and opportunities: a synthesis of the Eastern and Southern Africa situation in terms of past experiences, present and future opportunities in promoting nutrients use in Africa. Cali (Colombia): CIAT. The University of Queensland. QAAFI. CIMMYT.

Suzuki, K., Mastunaga, R., Hayashi, K., Mastumoto, N., Tobita, S., Bationo, A., Okada, K., 2016. Long-term effects of fertilizer and organic matter application on millet in Niger. Agron. J. 108, 1–11

Suzuki, K., Matsunaga, R., Hayashi, K., & Matsumoto, N. 2017. Agriculture , Ecosystems and

Environment Effects of long-term application of mineral and organic fertilizers on dynamics of nitrogen pools in the sandy soil of the Sahel region , Niger. "Agriculture, Ecosystems and Environment," 242, 76–88. https://doi.org/10.1016/j.agee.2017.03.004

Tabo R, Bationo A, Diallo Maimouna K, H. O. and K. S. 2006. Fertilizer micro dosing for the prosperity of the small scale farmers in the Sahel. *:* International Crops Research Institute for the Semi-Arid Tropics, No 23, 28.

Trust, L.A., 2007. Genstat. Lawes Agricultural Trust (Rothamsted Experimental Station), Rothamsted, UK.

van Reeuwijk, L.P., 1993. Procedures for soil analysis. Technical paper No 9, Fourth edition edited by the International Soil Reference and Information Center (ISRIC).

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter,and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

West, L. T., Wilding, L. P., Landeck, J. K. and Calhoun, F. G. 1984. Soil survey of the ICRISAT Sahelian Center, Niger, West Africa.