LONG-TERM EFFECT OF REDUCED FERTILIZER RATE AND INTEGRATED SOIL FERTILITY MANAGEMENT PRACTICES ON SOIL PROPERTIES IN SAHELIAN WEST AFRICA

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ABSTRACT

Fertilizer microdosing, the application of a reduced fertilizer rate next to the seed within ten days of sowing, and other Integrated Soil Fertility Management (ISFM) techniques including organic matter (OM) application and legume incorporation have shown potential for improving crop production of smallholder farmers in the Sahel of West Africa in short-term research. Little long-term research on the sustainability of these techniques has been conducted thus far, however. The objective of the current research is to determine the long-term effect of the microdosed rate of fertilizer at the Sadore research site in Niger running 16 years, as well as the impact of ISFM techniques at both Sadore and a 50-year running site at Saria, Burkina Faso on SOM dynamics and soil properties including pH, soil organic carbon (C), cation exchange capacity, electrical conductivity, total nitrogen (N) and phosphorus (P), and available P. SOM dynamics were investigated using the X-ray Absorption Near-Edge Structure (XANES) technique for C and N speciation. Yield regression under fertilizer treatments at Sadore was also calculated. Treatments at Sadore included three rates of fertilizer: control, microdosed rate of 15 kg N ha^{-1} and 4.4 kg P ha^{-1}, and 30 kg N ha^{-1} and 13.2 kg P ha^{-1} with P broadcasted and N applied using point placement. Crop residue and manure were also applied, each at 300, 900, and 2700 kg ha^{-1}. At Saria, ISFM treatments included two broadcasted fertilizer rates: 1) 100 kg ha^{-1} 14-23-14 (NPK) with 50 kg ha^{-1} urea and 2) NPK with an additional 50 kg ha^{-1} urea and 50 kg ha^{-1} KCl, with and without crop residue at 4800 kg ha^{-1}, or manure at 5000 kg ha^{-1} or 40000 kg ha^{-1}. As well, mixed cereal-cowpea cropping was compared to continuous cropping of millet at Sadore and sorghum at Saria. The microdosed rate at Sadore had significant yield benefits over the unfertilized soil; however, yield declined over time under both the microdosed and recommended fertilizer rates. Possible soil fertility-related drivers of yield decline include soil acidification, low SOM, and mining of nutrients not applied in fertilizer. Soil pH was improved with crop residue at the 2700 kg ha^{-1} rate at Sadore and manure at the 40000 kg ha^{-1} rate at Saria, which also increased SOC and CEC. C and N XANES data showed that soil treated with higher OM rates and reduced or no fertilizer was more enriched in aromatic-C, pyrrolic-C, N-bonded aromatics and amide-N, organic groups associated with lower levels of humification and/or greater input of available microbial substrate, and depletion of ketone- and phenol-C groups under continuous cropping also indicated greater levels of OM degradation. For sustainable soil

fertility management in the Sahel, applying the microdosed rate of fertilizer with manure and crop residue at as a high of rates as possible for smallholders, and including legumes into the cropping mix is recommended.

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DEDICATION

First of all, I dedicate this work to Jesus. I would not be who I am and where I am today without his friendship and selfless love. I also dedicate this work to my husband Levi Adams, who is so dependable and strong. It is a joy to be your wife! Finally, I dedicate this work to the many smallholder farmers that are living in poverty today, who have so much potential, and so few tools. I pray for the chains of poverty that hold you back to be broken and that my work and work like it would reach you to provide the tools you need to move forward.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

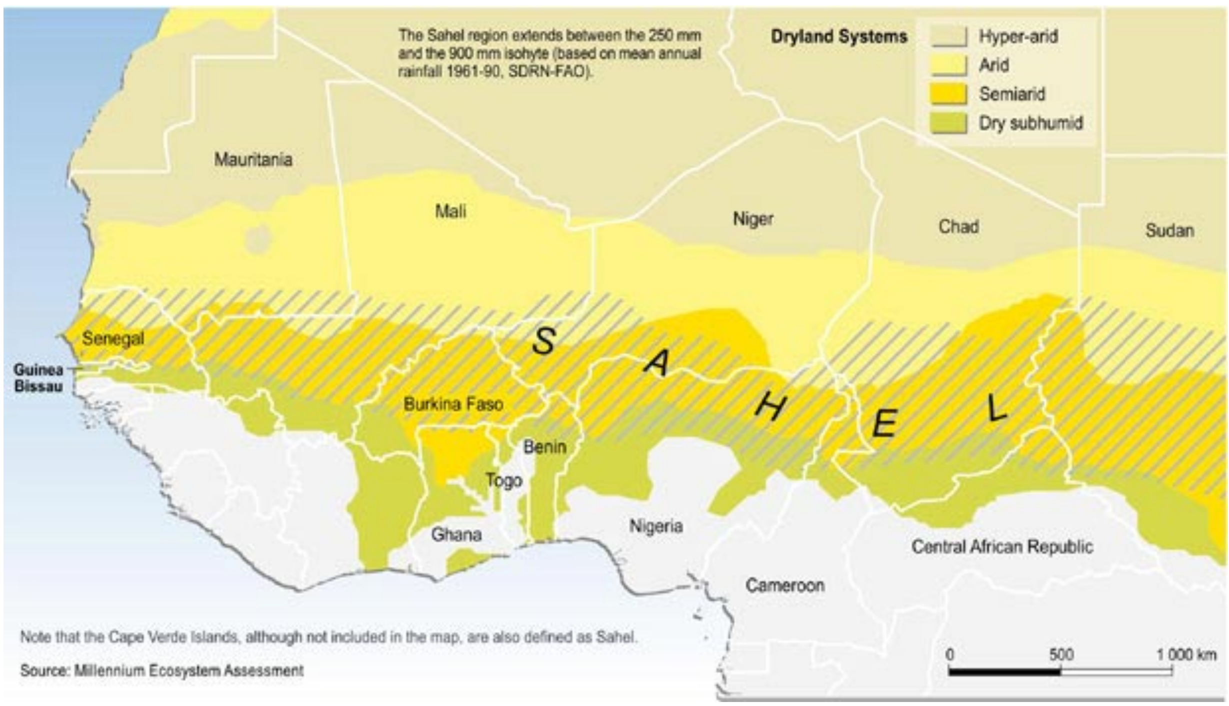
LIST OF ABBREVIATIONS

ISFM	Integrated Soil Fertility Management
SOC	Soil organic carbon
CEC	Cation exchange capacity
EC	Electro-conductivity
XANES	X-ray Absorption Near Edge Structure
FAO	Food and Agriculture Organization
SSA	Sub-Saharan Africa
UNDP	United Nations Development Program
HDI	Human Development Index
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics
INERA	Institut de l'Environnement et de Recherches Agricoles (Institute of Environment and Agricultural Research)
SOM	Soil organic matter
WRB	World Reference Base for Soil Resources
OC	Organic carbon
OM	Organic matter
TDM	Total dry matter
DAS	Days after sowing
NPK	Nitrogen-phosphorus-potassium fertilizer
CAN	Calcium ammonium nitrate
SSP	Single super phosphate
SGM	Spherical Grating Monochromator
CR	Crop residue
C:N	C:N ratio
TSBF-CIAT	Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture
MAT	Mean annual temperature
EDTA	Ethylene diamine tetra-acetic acid

1. INTRODUCTION

Food security is described by the Food and Agriculture Organization (FAO) (1996) as the stable access of individuals to sufficient quantities of safe and nutritious food. Sub-Saharan Africa (SSA) has the highest prevalence of food insecure people globally, as 26.8% of the population is considered undernourished, compared to the world average of 11.3% (Food and Agriculture Organization of the United Nations, 2014). To exacerbate the issue of hunger in SSA, crop production is increasing at only 1% per year (Chauvin et al., 2012). In SSA, reported cereal yields of about 1100 to 1500 kg ha^{-1} are half to a third of the world average of 3200 kg ha^{-1} (Lal and Stewart, 2010; Africa Progress Panel, 2014). Contrary to crop production, population growth in Sub-Saharan Africa is rapid. Sub-Saharan Africa is the most rapidly growing region in the world in terms of population, with an annual growth rate of 2.6%, compared to a 1.48% growth rate in Asia and a global growth rate of 1.44%. As well, Africa holds the highest population of children under the age of 15, and most of the world's future population growth will be in Africa (United Nations Department of Economic and Social Affairs, 2013). This rapid population growth has put pressure on land resources and led to a decrease or elimination of fallow periods and increased cropping of marginal lands (Saïdou et al., 2004; Abdoulaye and Sanders, 2005). Because this population boom is not matched by increased agricultural production, the number of undernourished people in SSA is increasing, which will lead to continual land degradation if immediate information-based action is not taken.

In the Sahel of West Africa (Fig. 1.1), issues of malnourishment, low crop production and environmental degradation are even more acute due to a harsh and unstable climate plagued with frequent drought and famine, with four food crises in the last ten years (2005-2015) (European Commission, 2015). Human welfare is low in the region, which includes Niger, Mauritania, Chad, Mali, Burkina Faso, The Gambia, Senegal, northern Cameroon, Nigeria, and Benin. The average Human Development Index (HDI) rank, a measure of welfare developed by the United Nations Development Programme (UNDP), for these Sahelian countries is 169 out of 187 countries compared globally. Burkina Faso and Niger, the countries of specific interest to this research have exceptionally low HDI's, at 181 and 187 respectively (UNDP, 2014). Low soil fertility and unreliable rainfall patterns in the Sahel, along with extremely high fertilizer prices, lack of credit, high labor requirements, and little access to extension services make soil fertility management extremely difficult for subsistence level farmers, which comprise 90% of the population in the region (Saïdou et al., 2004; Abdoulaye and Sanders, 2005). As in the rest of Africa, population pressure has lead to the breakdown of the traditional rotating cultivation and fallow system and there is little opportunity to expand cropped area (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008). To address hunger in Africa in general and the Sahel in particular, production must be increased without degrading the land, through sustainable



agriculture intensification.

Fig. 1.1. Map of the Sahelian region of West Africa (Zeng, 2003).

Due to the poverty and resource scarcity faced by smallholder Sahelian farmers, rapid agricultural intensification and investment in recommended rates of fertilizer is not financially feasible (Aune and Bationo, 2008; Vanlauwe et al., 2010). Agricultural intensification in Africa follows a step-by-step development pathway, described as a development "ladder" (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008). Instead of rapid increase in fertilizer use and other capital investments, farmers take small, low-risk steps, with the goal of maximizing their use of technologies and inputs available within their means to step to the next rung of the ladder (Aune and Bationo, 2008; Tabo et al., 2007). First steps in the ladder require increased labor and better stewardship of local resources, followed by adoption of low-cost inputs, with gradually higher capital investment as capacity is built and production increases. Integrated Soil Fertility Management (ISFM) is a set of locally adapted practices that include fertilizer application, organic amendments, and use of improved plant genetics, to maximize agronomic use efficiency and crop production (Vanlauwe et al., 2010). As with the stepladder concept of agricultural intensification, ISFM adoption also follows a stepwise pattern, with adoption of more intensive ISFM practices as soil fertility and financial capacity is built. Many ISFM practices including mineral fertilizer application, manure and crop residue amendment, and incorporation of N-fixing legumes into cropping systems may have great benefits for cropping systems in West Africa; however, research on the long-term effects of ISFM is required to quantify these benefits.

Fertilizer microdosing is the application of a reduced rate of fertilizer next to the seed within ten days of sowing. Microdosing has been proposed as one component of ISFM and one step in the development ladder (Abdoulaye and Sanders, 2005; Vanlauwe et al., 2010). The low capital investment of less than 4 kg P ha^{-1} has been found to more than double yields in the Sahel compared to no fertilizer use, and minimizes risk to the smallholder compared to applying recommended rates (Twomlow et al., 2008). Microdosed point-placement increases fertilizer use efficiency compared to broadcasted fertilizer at higher rates, and provides an economic return to farmers, allowing farmers to gradually increase their investment in inorganic fertilizer and other soil amendments, developing their agricultural practices (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008). Microdosing is a promising technique for maintaining soil fertility and food security improvement in the Sahel; however, little research has been done thus far to determine the long-term sustainability of microdosing. The microdosed rate is typically less than nutrient removal with harvest; however, researchers expect that farmers will apply more fertilizer when they see returns from microdosing, and thus the negative nutrient balance will be temporary (Aune and Bationo, 2008). Farmers may not increase fertilizer rates beyond microdosed rates over the long-term if they do not have access to a steady fertilizer supply, or if money set aside for fertilizer purchase must be used to pay for a child’s schooling or a medical emergency. The long-term effect of fertilizer microdosing on soil quality and productivity must be determined before microdosing can be incorporated into an ISFM strategy for sustainable intensification in the Sahel. Research into the long-term sustainability of reduced rate microdosing and other ISFM practices separately and together is important for sustainable intensification of crop production and prolonged food security in the Sahel and rest of Sub-Saharan Africa.

The objective of the research in this thesis is to determine the long-term impact of the reduced microdosed rate of fertilizer and other ISFM practices on soil fertility and carbon (C) and nitrogen (N) dynamics at two long-term research sites in Sahelian West Africa. In order to achieve these objectives, the thesis is organized into two manuscript chapters. The first chapter examines the long-term effect of the reduced microdosed rate of commercial fertilizer in comparison with the recommended rate and no fertilizer. As well the interaction of the different fertilizer rates with crop residue and manure application is analyzed to determine ways to further improve sustainability. The second chapter covers the long-term impact of a variety of ISFM practices, including manure and crop residue application alone and in combination with fertilizer, and mixed cropping with legumes, as well as cultivation. Two long-term research trials were used in the studies; one established in 1993 at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Sadore, Niger, and the other established in 1965 in Saria, Burkina Faso by INERA (Institut de l'Environnement et de Recherches Agricoles). Only the Sadore site compares a microdosed rate of fertilizer to recommended rate, thus this site is the focus of the first manuscript. Both the Sadore and Saria trials include a variety of ISFM treatments, thus soil from both sites is utilized in the second manuscript. The two research chapters follow a literature review intended to give context to the research questions and methods used. Finally a synthesis and conclusions chapter is used to draw general conclusions from the results of the studies and offer recommendations for policy and future research.

2. LITERATURE REVIEW

2.1 Sahelian Soil

2.1.1 Soil characteristics and formation

The main soil types in the Sahel provide significant challenges to crop production due, in part, to their low nutrient retention capacity. In general Sahelian soils are characterized by low organic matter, depletion of base cations, and an accumulation of unreactive kaolinitic clay minerals and Fe and Al oxides and hydroxides. These characteristics lead to low pH and cation exchange capacity (CEC), weak soil structure, and overall low inherent soil fertility (Jones et al., 2013, Juo and Franzluebbers, 2003). The factors and processes involved in tropical soil formation differ greatly from those in temperate regions. Generally, tropical soils are formed on more acidic sandstone, quartzite, or granite parent material with lower inherent fertility than the basalt, limestone and glacially derived parent material found in temperate regions (Jones et al., 2013; Juo and Franzluebbers, 2003). Tropical soils are much more weathered than temperate soils due to a much longer time since glaciation, and a warm climate year round (Muehlig-Versen et al., 2003). Soil weathering processes including the leaching of silicate minerals and base cations from the soil solution, weathering of primary rock minerals to kaolinite, or Al and Fe hydroxides such as gibbsite and goethite, and sorption of P to Al and Fe hydroxides. These processes increase acidity, lower CEC, and deplete the soil's nutrient stores (Tan, 2011; Juo and Franzluebbers, 2003). As well, Sahelian soils are highly phosphorus (P) deficient, because of low total P reserves and soil organic matter (SOM) content and a high degree of weathering of P from soil parent material (Juo and Franzluebbers, 2003). The above factors and processes have led to development of soils characteristically low in soil nutrients, with a low capacity to retain nutrients and buffer soil pH.

The dominant clay mineral in sandy Sahelian soil is kaolinite ($Si_2O_5Al_2OH_4$). As a highly weathered secondary mineral, it presents challenges for crop production. Kaolinite's 1:1 phylosillicate structure, lack of isomorphic substitution, and small surface area means there are few ion adsorption sites (Tan, 2011). One beneficial characteristic of kaolinite is that it does not fix P as strongly as other minerals found in tropical soils; however, kaolinite is not able to retain P and other nutrients well (Muehlig-Versen et al., 2003). Kaolinite is able to retain some $H_2PO_4^-$ when pH is low, however, because Al-OH groups on mineral edges are protonated and thus positively charged (Juo and Franzluebbers, 2003; Fageria, 2009). In the Sahel, kaolinite rich soils are prone to surface crusting and compaction, wind erosion, drought stress, nutrient deficiencies, and Al toxicity, as well as acidification with continued fertilizer use (Juo and Franzluebbers, 2003). Kaolinitic-rich Sahelian soils present many challenges that smallholder farmers must overcome to achieve food security.

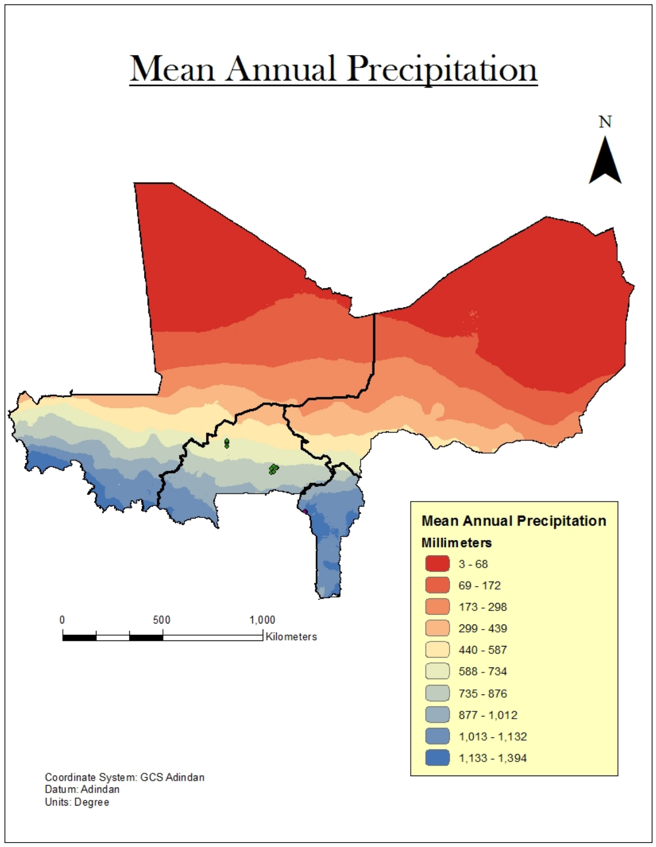


Figure 2.1. Mean annual precipitation in the Sahelian region (Minielly and Rehman, unpublished).

2.1.2 Agricultural soil types

The soil types most suitable for agriculture in the Sahel, according to the World Reference Base for Soil Resources (WRB), are Arenosols and Lixisols. Soil type changes from Arenosols to Lixisols as mean annual precipitation increases from north to south (Fig. 2.1). In arid to semi-arid southwestern Niger, the dominant soil type is Arenosols (Jones et al., 2013). Arenosols are formed from aeolian sand deposits and thus have low water and nutrient retention, and low nutrient content. They are commonly deficient in micronutrients, sulfur (S), and potassium (K), and are prone to wind erosion because of their poor structure. Applied fertilizer is easily leached (Jones, 2013; Bationo et al., 2012a). Moving southwest towards Burkina Faso, change in parent material, decrease in average temperature, and increase in precipitation and vegetation growth allows increased biological and chemical weathering. Increased moisture leads to clay mineral illuviation, forming the kaolinite-enriched B horizon characteristic of Lixisols, the dominant soil type in Burkina Faso (Jones et al., 2013; Bationo et al., 2012a). Lixisols are deeply weathered, high in Fe and Al oxides, and dominated by kaolinitic clays and gibbsite, with a low nutrient retention capacity (Bationo et al., 2012a). Lixisols generally have a higher base status than other tropical soils, and thus are less prone to acidity and Al toxicity. They are suitable for agricultural production but will become rapidly depleted in nutrients if fertilizer and organic matter are not applied (Bationo et al., 2012a; Jones et al., 2013). The low nutrient retention capacity and low inherent fertility of agricultural soils in the Sahel mean that nutrients for crop growth must be provided by outside sources. To ensure the productivity of these soils, proper soil fertility management that includes mineral fertilizer application is essential.

2.2 Soil Nitrogen, Phosphorus, and Carbon Function and Cycling in the Sahel

Nitrogen is a main component of many organic compounds including amino acids and proteins, nucleic acids, enzymes, and chlorophyll, and is an essential nutrient for plant physiology (Fageria, 2009; Tan, 2011). The main N inputs in agricultural systems include inorganic fertilizer, manure, and crop residue application, biological N fixation by legumes or specific soil microorganisms, and N deposition in rainfall. In the Sahel, N inputs to the soil are often low because of low access to inorganic fertilizer, scarcity of manure, and competing uses for crop residue as animal feed or cooking fuel (Buerkert and Hiernaux, 1998). Nitrogen cycling is complex and affects soil functioning in the Sahel in several ways. First, plants and soil microbes take up N added to the soil most commonly in the inorganic nitrate (NO_3^-,) and ammonium (NH_4^+) forms, and microbes also mineralize organic crop residues and manure and immobilize the N in their biomass. Microbial immobilized N is released as plant available N as microbes die and their biomass is recycled (Fageria, 2009). Soil tillage, which is common in the Sahel, may aerate soil, stimulating microbes to mineralize N, lowering soil N content (Mando et al., 2005). Nitrification is the conversion of NH_4^+ to NO_3^- and releases H^+ ions into the soil, lowering soil pH, increasing soil acidity and potentially inhibiting soil functioning (Fageria, 2009; Hatfield and Sauer, 2011). Soil erosion and surface runoff from soil crusting are other major N-loss pathways in the Sahel, and are caused by low SOM and poor soil structure, which is accentuated with tillage (Buerkert and Hiernaux, 1998). As well, NO_3^- is mobile in the soil solution and thus can be leached from the rooting zone. Leaching is high in the Sahel because the sandy soils have a high infiltration capacity and hydraulic conductivity (Buerkert and Hiernaux, 1998). N can also be volatilized from soil as NH_3, which is especially common when rain does not soon follow surface application of NH_4^+ fertilizer. This pathway of N loss may be of concern in the Sahel due to variable rainfalls, but can be minimized through precise placement of fertilizer in the soil, as in microdosing (Fageria, 2009). There are many potential pathways for loss of scarce N fertilizer from soil in the Sahel, thus research should focus on improving N use efficiency.

As with nitrogen, phosphorus (P) is also an essential macronutrient for cropping in the Sahel. P is needed for storage and transfer of energy, root growth and stem culm strength, and for N_2 fixation in legumes (Fageria, 2009). The soil P is derived from soil parent material through dissolution of P bearing minerals like apatite or is added as a component of inorganic fertilizer or manure. The P has low mobility in the soil solution and is easily fixed to clay or complexed with organic matter, thus much applied soil P is not directly available for plant use (Juo and Franzluebbers, 2003; Fageria, 2009; Tan, 2011). Transformations and plant uptake of P are controlled by climatic factors such as soil temperature and moisture, and soil factors such as texture, SOM content, soil pH, and concentration of P in the soil solution (Fageria, 2009). The SOM content is important for P retention in the soil system because organic matter can absorb phosphates (Tan, 2011). Phosphorus is very important for soil functioning but is limited in the Sahel.

Organic carbon (OC) is very important for soil functioning, improving many physical, biological, and chemical characteristics of the soil. Soil carbon improves structure, promoting aggregate formation and water retention, which prevents erosion, surface crusting and compaction. Carbon provides an energy source for microbes and improves soil aeration, increasing biological activity and the cycling of nutrients. Soil organic carbon (SOC) also increases cation exchange capacity (CEC) by providing pH dependent exchange sites on humus molecules that retain nutrients. All of the above benefits of C improve and sustain crop yield in the tropics (Delgado and Follett, 2002; Fageria, 2009; Gentile et al., 2013). Increasing and maintaining soil carbon thus is an essential component of agriculture development and food security in the Sahel. The main C inputs to soil in smallholder agriculture in the Sahel include organic matter (OM) inputs such as manure, crop residues, plant detritus, microbes, and closer to the farm settlement, human waste and food compost (Tittonell et al., 2008). The microbial community mineralizes the C in these OM inputs for energy, releasing respired CO_2 to the atmosphere, and returning organic C to the soil in their waste or biomass to ultimately form more stable humus. Microbes eventually degrade organic C into humus, which is further exploited by microbes for nutrients and energy (Delgado and Follett, 2002; Grandy and Neff, 2008; Puttaso et al., 2013). The C cycle is very important to soil fertility and functioning and is driven by microbial degradation of organic matter inputs.

The C cycle specifically influences soil nutrient cycling and soil fertility in several ways. First, the breakdown of C inputs into humus leads to the release and recycling of nutrients contained in the OM for plant use, mainly N, P, S, as well as Zn and Cu (Delgado and Follett, 2002). The SOM also influences nutrient cycling through buffering pH and creating a pH dependent surface charge that increases nutrient retention at higher pH levels. Because of SOM oxidation, humus is rich in carboxyl ($COOH^-$) and phenol (OH^-) groups that are able to release or accept H^+ ions as their concentration changes, buffering acidity and its impact on crop growth, and contributing to cation retention at certain pH levels (Singer and Munns, 2006). Because humus is colloidal, it is also able to adsorb to clay particles and form stable aggregates with clay and other SOM particles. These processes improve soil structure and quality, and protect OM from further degradation (Singer and Munns, 2006). C cycling impacts soil fertility and nutrient cycling in many ways, and soil nutrients, especially N interact with C to impact soil organic matter (SOM) dynamics as a whole.

2.3 Soil Organic Matter Dynamics

SOM contains C, N, P and many other compounds and nutrients, and its deposition and decomposition is important for soil fertility. Microbes break down SOM in a decomposition sequence, and specific C and N containing organic compounds are present at certain points in the sequence (Lutzow et al., 2006; Wickings et al., 2012). Within the humus fraction there are forms or species of C and N with different characteristics such as charge, oxidation state, and availability in the soil solution (Conklin, 2005). Some species of C and N are plant derived, indicating soil decomposition is less advanced, and other species are microbially derived, indicating greater OM turnover (Gillespie et al., 2014b). The decomposition sequence and subsequent soil C and N speciation is driven by environmental conditions that impact microbial activity, which are determined by inherent soil and climatic characteristics as well as soil management practices (Lutzow et al., 2006; Singer and Munns, 2006; Wickings et al., 2012). Some soil properties such as soil temperature, water content, structure, texture, and mineralogy are difficult to manipulate in smallholder rain fed agriculture (Singer and Munns, 2006). Soil texture is especially influential on organic matter (OM) degradation in the Sahel, as there are few fine soil particles in the dominantly sandy unreactive soil to form and physically protect OM aggregates and stabilize C (Feller and Beare, 1997; Grandy et al., 2008; Grandy and Neff, 2008). While inherent soil properties are difficult to manipulate, soil pH, aeration, OM input, and nutrient content can be managed, impacting microbial OM decomposition and C and N speciation (Singer and Munns, 2006). Soil tillage increases exposure of soil microbes to oxygen, also stimulating microbial C and N decomposition (Hatfield and Sauer, 2011). As well, the quantity, C:N ratio, and composition of soil inputs all impact microbial C and N dynamics (Rasche and Cadisch, 2013; Singer and Munns, 2006). N fertilizer addition also leads to the degradation of certain C and N groups through lowering the C:N ratio of the soil (Neff et al., 2002). Analytical techniques exist to study C and N speciation, useful for determining the impact and sustainability of different management techniques.

2.4 Studying Carbon and Nitrogen Dynamics Using XANES

While quantifying SOC and N in the bulk soil through wet chemistry techniques is useful, revealing the type of C and N molecules contained in the soil organic matter can also help better understand soil nutrient dynamics (Gillespie, 2013). C and N speciation can be determined through X-ray Absorption Near Edge Structure (XANES) spectroscopy, in which soil samples are exposed to photons across an energy range specific to that element. The light excites a core electron, which is then promoted to a higher energy orbital, leaving a core electron hole. An electron at a higher orbital relaxes to fill the hole, and energy is released as photon fluorescence or electron emission. Beamline detectors measure both these parameters as a proxy for the number of photons absorbed by a compound. The energy at which these photons are absorbed gives information on the bonding structure of molecules being measured and the functional groups present (Myneni, 2002). The output of C and N XANES is a spectra graph that represents a fingerprint of the specific organic C or N compounds in a sample. Peaks at specific energies of the spectra for a specific element represent certain species of that element, determined by reference compounds in the literature. Fig. 2.2 is an example of reference compounds used to determine carbon speciation. The XANES technique has yet to be used to study the effect of soil fertility treatments on soil C and N speciation in African soil. In fact, only one case was found in the literature where XANES was used to study African soil in general (Solomon et al., 2005). Thus use of XANES in this current research will help further develop the technique as a tool for characterizing organic C and N forms in diverse soil types and help reveal C and N dynamics as affected by soil fertility management in the Sahel.

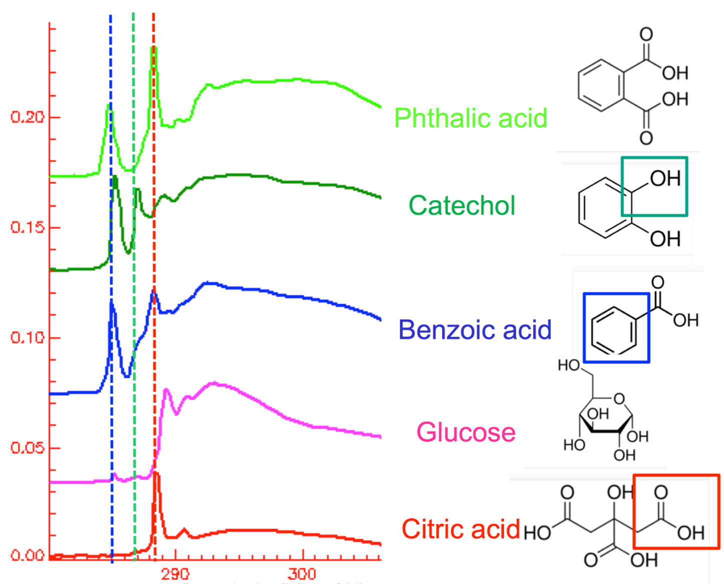


Fig. 2.2. C XANES spectra of standard carbon containing compounds. (J.J. Dynes, unpublished data).

2.5 Current Boundaries of Fertilizer Microdosing Research

Much research has been done thus far in the Sahel and greater Africa on microdosing, with the main research focus being to optimize the technique. Research has been completed to determine the yield response of microdosing across growing seasons, in different soil types or climates, under both farmer and researcher management, in various cropping systems (Buerkert and Hiernaux, 1998; Tabo et al., 2007; Twomlow et al., 2008; Bagayoko et al., 2011). Results from this research indicate that reduced rates of nutrients applied precisely using the microdosing approach does not optimize yield but increases fertilizer use efficiency (yield produced per unit of fertilizer added) in comparison to the conventional broadcast method of application in a variety of agricultural environments (Buerkert and Hiernaux, 1998; Muehlig-Versen et al., 2003; Twomlow et al., 2008). Microdosed P at the planting site increases P availability to the seedling, stimulating root development, early season plant growth, and stand establishment in comparison to broadcast application, doubling phosphorus use efficiency in some instances (Muehlig-Versen et al., 2003; Valluru et al., 2010). Certain aspects of microdosing have been researched to date, but there are areas where more research is needed, both of which are discussed below.

2.5.1 Yield response of microdosing

Crop yield response to microdosing over the short-term has been researched across Sub-Saharan Africa. Yield results from pearl millet trials at several controlled research sites in the Sahel showed increases in grain yield over the unfertilized control of 27% to 53% under microdosing at 3-4.5kg P ha^{-1} and increases of 50-113% at 4 kg P ha^{-1} (Buerkert et al., 2001; Muehlig-Versen et al., 2003). In Sudan, rates as low as 1.5 kg of N and P ha^{-1} increased yield by 31% in millet and 50% in sorghum, and at 6 kg ha^{-1}, millet yield increased by 47%, and sorghum increased by 110% compared to the unfertilized control (Aune and Ousman, 2011). A trial in Ethiopia there was no significant difference in yield between three microdose treatments at 13, 24, and 37 kg N and P ha^{-1} and one banded treatment at 46 kg N and P ha^{-1} (Sime and Aune, 2014). Compared to the control, total dry matter (TDM), which is important for building up SOM, increased by 48% at a rate of 3kg P ha^{-1} and 64% at a rate of 5kg P ha^{-1}. These TDM results were 72% and 81% respectively of TDM production at the recommended rate (Bagayoko et al., 2011). Another controlled microdosing trial in the Sahel did not have improved production of TDM in legumes (Buerkert et al., 2001).

Grain and stover yield improvements were also seen in farmer-managed microdosing trials across the Sahel. Microdosed rates of 3-9 kg P ha^{-1} increased millet and sorghum grain yield by 36-130% and stover yield increased between 36% and 124% compared to an unfertilized control across several Sahel trials (Buerkert and Hiernaux, 1998; Buerkert et al., 2001; Tabo et al., 2007; Aune and Bationo, 2008; Bagayoko et al., 2011; Aune and Ousman, 2011). There was no significant yield difference between microdosing and the recommended dose in some farmer-led research as well (Tabo et al., 2007; Bagayoko et al., 2011). Another benefit of microdosing outside of yield was that small doses of P fertilizer reduced invasion of the parasitic *Striga hermonthica* weed that inhibits millet production in the Sahel (Jamil et al., 2014). There has been extensive research showing the positive yield response of varied microdosing rates in different regions of the Sahel and the rest of Africa with different crops, under many different management practices.

2.5.2 Effect of timing and management practices on yield response of microdosing

Along with yield response research, work has also been done to understand the nutrient dynamics of microdosing under different conditions to optimize the technique. Research includes quantifying the effect of previous land management, as well as timing of microdosed rates and relative effects of microdosed N and P on yield. Microdosed P at 10 kg ha^{-1} improved yield more than N at the same rate across several trials in Africa and South America, indicating the importance of P application (Van der Velde et al., 2013). The most beneficial timing for microdosing is reported to be from the time of sowing up to 10 days after sowing (DAS) (Hayashi et al., 2008; Valluru et al., 2010). Microdosed fertilizer may also be applied later in the growing season, as late as 57 DAS, and still obtain a yield benefit, although it may be a smaller improvement than an earlier application. In one study however, yield was not significantly different, or even higher in a later application than when applied directly after sowing if the fertilizer application was followed by rainfall (Hayashi et al., 2008). Flexibility of microdose timing application benefits farmers with a shortage of labour or access to fertilizer at sowing, or who want to minimize risk by delaying fertilizer application to see if there will be sufficient rainfall (Hayashi et al., 2008). As well, microdosing was found to be the most beneficial on soils with low fertility, where there was no previous manure application (Bielders and Gérard, 2015). Because of the scarce availability of fertilizer for smallholder farmers, this research has been beneficial for determining the best way to apply microdosed fertilizer.

The effect of other management practices on yield response and nutrient dynamics in microdosing has also been studied. Seed priming, in which seeds are soaked in water for 8-10 hours before sowing, benefited microdosed yield in comparison to microdosing on its own (Aune and Bationo, 2008; Aune and Ousman, 2011). Certain rainwater harvesting techniques also interact with microdosing to further improve yields (Palé et al., 2009). The synergy of organic inputs and micro dosed fertilizer were studied at one site, and a rate of 8.5 kg N ha^{-1} with 6000 kg ha^{-1} of manure benefited yield more than a high fertilizer rate of 62 kg N ha^{-1} without manure (Ncube et al., 2006). The joint application of microdosed P with rock phosphate provided a better long-term P management strategy, as seed placed P provided early season benefits, while rock P released P over the growing season and in the following growing seasons (Muehlig-Versen et al., 2003). Based on research thus far, the benefits seen with microdosing can be improved with the addition of seed priming, rainwater harvesting, and application of manure or rock phosphate; however, more research on the benefits of these and other management practices in combination with microdosing is still needed.

2.5.3 Profitability and adoption of microdosing

Research has been conducted to determine the profitability and factors affecting adoption of microdosing. The conclusion of many of the studies reviewed is that because of the small investment and high efficiency of microdosing, it is a profitable technique for farmers (Abdoulaye and Sanders, 2005; Tabo et al., 2007; Twomlow et al., 2008; Aune and Ousman, 2011). Farmer-managed trials in which smallholders are exposed to the benefits of the microdosing technique have led farmers to increase their fertilizer rates beyond microdosing and experiment with different combinations of inorganic and organic amendments and soil conservation techniques. Therefore in the field, microdosing is acting as an initial step in agricultural development (Abdoulaye and Sanders, 2005; Twomlow et al., 2008). According to the literature, short-term microdosing not only benefits crop production, but also is improving returns to farmers, an important component of sustainable agricultural development and food security. Comparing three different microdosing rates, the lowest microdose rate was most profitable and least risky for farmers and compared to the control, the lowest microdose rate had an average yield increase of 37% across three sites (Sime and Aune, 2014). Overall research shows microdosing is profitable and lowers risk for Sahelian smallholders.

2.5.4 Impact of microdosing on soil fertility and environmental sustainability

While it is clear that microdosing offers yield and return increases to farmers over the short term, if the rate of nutrients added in microdosing is less than the nutrients exported at harvest, the soil is expected to become nutrient-depleted over time. Potential for nutrient mining with microdosing, and the impacts of microdosing on soil quality is scarcely mentioned in the literature. Some researchers noted that the low quantities of fertilizer used in micro-dosing do not meet nutrient requirements, meaning that they likely lead to a highly negative nutrient budget and depletion of nutrient stores, restricting yields, especially if there is no alternative source of nutrient or OM applied (Buerkert et al., 2001; Muehlig-Versen et al., 2003; Aune and Bationo, 2008; Twomlow et al., 2008). Buerkert et al. (2001) noted that microdosed application only supplies a portion of the nutrients the plant requires, so it should only be used as a first step in a long-term soil fertility management plan. Some other researchers briefly discussed the potential for microdosing to increase SOC because microdosing increases dry matter production in comparison to unfertilized soil (Buerkert et al., 2000). Bagayoko et al. (2011) and Beurkert et al. (2001) measured stover yield instead of grain yield in part because of the implications of microdosing for soil C inputs. If residue from microdosed crops is left in the field, microdosing may lead to increased SOM and improved soil quality (Buerkert et al. 2001; Aune and Bationo, 2008; Bagayoko et al., 2011). Thus some mention was made in the literature of the influence of microdosing on soil quality and environmental sustainability; however, there is much more work that needs to be done.

In reviewing the literature, research focus has been on the yield benefits of microdosing and agronomic optimization. The main variable measured in all of these trials is annual grain and stover yield response, and total dry matter production. Not only yield response, but yield trends over several years must be assessed to determine the sustainability of microdosing, and yield trend can only be determined via long-term experiments (Bielders et al., 2002b; Janssen et al., 2011). There have only been short-term research trials on microdosing thus far, and no trial has evaluated impacts for longer than 5 years. Along with yield parameters, effect of microdosing on soil properties must also be analyzed. Only one study included the measurement of soil properties, and nutrient concentration of plants was a component of another trial (Muehlig-Versen et al., 2003; Ncube et al., 2006). The long-term effect of microdosing on soil properties must be studied to determine if microdosing is a sustainable technique for soil quality maintenance. Additionally, very little research was done on the interaction of microdosing and other management practices such as manure or crop residue amendment and crop rotation. Only one study assessed the impact of application of organic amendments on microdosing yields, and one other trial included a cereal-legume rotation component (Buerkert et al., 2001; Ncube et al., 2006). Long-term effects of other management practices on microdosing are important to consider in sustainability of microdosing. The research work highlighted above has been foundational for developing and encouraging the adoption of the microdose technique for impoverished smallholder farmers. The aim of my current research is to build on the work done thus far by adding the important component of soil resource and environmental sustainability to the body of microdosing research.

2.6 Results from Long-Term ISFM Soil Fertility Studies

As discussed in the introduction, agriculture intensification in the Sahel is successful when approached as a stepladder, rather than promoting adoption of all practices at once, and microdosing is one rung in the ladder. Integrated Soil Fertility Management (ISFM) is a group of practices including the combined use of inorganic and organic fertilizers, use of good crop germplasm, and mixed cereal-legume cropping systems, which are also steps in the agriculture development ladder (Vanlauwe et al., 2010). As with microdosing, it is important to study the long-term effects of ISFM to establish its relationship to future food security through its impacts on soil quality. Important chemical indicators of soil quality include pH, OC, CEC, total and available P, and total N (Bielders et al., 2002a; Van Eerd et al., 2014). Long-term trials, 5-10 years or greater in length (Reynolds et al., 2014), are important because the impact of long-term treatments on these soil chemical properties is analyzed on a similar time-scale to real-life farming, where the same practices may be carried out for a farmer's working life (Bationo et al., 2012b; Reynolds et al., 2014). Although no long-term research on the effect of microdosing exists, some research exists on the long-term effects of different ISFM practices including fertilizer application, organic matter amendment, and crop rotation, as well as tillage on yield trends, soil quality, and nutrient dynamics. Results from long-term studies applicable to the current research, in which yield trends and soil quality parameters are assessed, are synthesized below.

2.6.1 Overall treatment trends

In the majority of long-term research trials in Sub-Saharan Africa, a decline in yield over time for each treatment from the onset of cultivation was observed (Bado et al., 2012; Bationo et al., 2012b; Kibunja et al., 2012). A reduction in SOM from the baseline level was seen in the same trials and continuous cultivation was practiced at each site, thus the decline in yield may be a result of SOM decline due to rapid OM mineralization under tillage (Bationo et al., 2012b; Kibunja et al., 2012). The reduction in SOM and yield decline was not seen, however, with the joint application of cattle manure and PK fertilizer at 37-11-6 (NPK) kg ha^{-1} for fertilizer and 54 kg N ha^{-1} and 9.3 kg P ha^{-1} as manure in one study, because the amount of OM added to the soil in the manure was enough to offset losses from cultivation (Bado et al., 2012). Research indicates there is a threshold level for OC, below which yield may be negatively impacted. To sustain yield and SOC levels, accumulation rates need to be higher than decomposition rates (Janssen et al., 2011). Conservation tillage is an important practice to prevent loss of soil nutrients and water, and to maintain SOM levels and microbial activity at the soil surface (Fageria, 2009). Reducing or eliminating tillage may be a sustainable soil management practice in the well-drained, low OM soils of the Sahel.

2.6.2 Application of N and P

In the tropics, a positive yield response to increased fertilizer rate compared to unfertilized treatments was seen in several long-term trials (Bationo et al., 2012b). Yield increased with fertilizer rate in a trial at Sadore, Niger (Abdou et al., 2012). The yield response to P was at least 40% higher than the response to N in several trials, indicating that P is more limiting in the region (Adamou et al., 2007, Kihara et al., 2012). In the long-term studies consulted, there was little analysis of crop yield trends as a result of fertilizer application. One paper did conclude, however, that treatments involving organic matter and fertilizer sustained yield better than fertilizer alone (Kibunja et al., 2012). From these results, application of mineral fertilizer, especially P, improved yield response when compared to untreated, and fertilizer with organic matter may sustain long-term yield better than fertilizer alone.

Long-term application of N and P fertilizer improved SOC at several temperate sites as a result of increased biomass production. SOC increase was highest with application of N, with or without P, and in the top 30 cm of the soil profile (Guo et al., 2007; Jagadamma et al., 2007; Mazzoncini et al., 2011; Congreves et al., 2014; Williams et al., 2014). However, in only a few tropical trials did SOC increase with increased fertilizer rate (Kihanda et al., 2012); in others SOC decreased with increased fertilizer rate (Bationo et al., 2012b). The difference between temperate and tropical trials is likely because cooler temperatures in temperate regions result in lower biodegradation rates, which are more conducive to OM accumulation. As well, soil N is lower in the tropics, thus addition of readily available fertilizer N to the system may lower C:N and stimulate microbial C mineralization. A decrease in pH over time was observed with increased rate of NPK as a whole, and with N fertilizer alone, in both the tropical and temperate trials (Divito et al., 2011; Bado et al., 2012; Kibunja et al., 2012; Williams et al., 2014). The application of N and P fertilizer in long-term trials led to decreased pH at all sites and SOM decrease in the tropics, which indicates degrading soil quality. Thus long-term application of mineral fertilizer alone likely is not a sustainable farming practice in the Sahel.

2.6.3 Joint application of inorganic and organic amendments

Applying organic and inorganic fertilizers together is considered a pillar of integrated soil fertility management for smallholder farmers because it improves fertilizer use efficiency (Vanlauwe et al., 2010). Applying fertilizer to manure or crop residue amended soil lowers the C:N, supplying microbes with the N necessary to break down organic materials while preventing leaching losses of inorganic N (Rasche and Cadisch, 2013). The inorganic fertilizer application meets immediate nutrient requirements and the organic matter provides a store of slow-release nutrients (Fageria, 2009). In the short term, synchronized application of crop residues and inorganic N improves soil aggregation, increases SOC, and stabilizes soil N, although less N and OC is stabilized in sandy soils than finer-textured soils (Gentile et al., 2013). Joint application may also reduce acidification commonly seen with prolonged N fertilizer application on kaolinitic soils (Juo and Franzluebbers, 2003). In several long-term tropical trials, highest yields were observed with combined organic and inorganic fertilizer (Bationo et al., 2012b; Bado et al., 2012). Manure application also improved fertilizer use efficiency at a trial in Burkina Faso because of improved soil structure and water retention (Mando et al., 2005). The combination of manure and inorganic fertilizer was found to be the most economical and sustainable treatment in many long-term trials in the tropics (Bado et al., 2012; Bationo et al., 2012b; Kibunja et al., 2012). Joint application of manure or crop residue with inorganic fertilizer increases nutrient use efficiency and relieves socioeconomic constraints, and thus may be key to improving the sustainability of soil fertility management in the Sahel.

2.6.4 Manure amendment

Application of manure alone provided varying yield, soil quality, and nutrient cycling benefits at long-term research sites across Sub-Saharan Africa. Yield was improved with manure amendment compared to unamended soil at several sites, and yield increased with increasing manure rate (Mando et al., 2005; Abdou et al., 2012; Bado et al., 2012; Bationo et al., 2012b). Manure also sustained long-term sorghum and millet yield better than inorganic fertilizer application at one research site in Kenya due to a residual manure-P effect (Kihanda et al., 2012). Manure application also led to higher OC and improved acidity parameters in comparison to fertilizer application in one trial (Bado et al., 2012). However, in another trial, application of fertilizer and manure had similar long-term effects on SOC, but pH increased from the baseline with manure and decreased with fertilizer (Kibunja et al., 2012). Manure increased SOC compared to unmanured treatments most significantly at the beginning of trials. Accumulation of SOC decreased over time, and after long-term treatment at several sites there was little difference in SOC between manure and fertilizer (Mando et al., 2005; Bado et al., 2012; Bationo et al., 2012b; Kihanda et al., 2012). In terms of soil nutrients, manure application had the highest total N and available P of all treatments in several trials (Bado et al., 2012; Bationo et al., 2012a, Kihanda et al., 2012). One problem with manure amendment mentioned in the literature is that the amount required to sustain yields is often higher than is feasible for smallholder farmers to apply (Bationo et al., 2012a). Although manure may provide yield and soil quality benefits, under the constraints faced by smallholders, manure application alone may not be a realistic option, thus the integrated use of fertilizer and manure would appear to be a better soil fertility management practice.

2.6.5 Crop residue amendment

Crop residues in tropical conditions provide many benefits to the soil, including improved root growth, increased availability of P, molybdenum, and potassium (K), and better modulation of soil temperature (Buerkert and Hiernaux, 1998). In long-term trials in Sub-Saharan Africa, application of crop residues had mixed effects on yield. In some cases residues increased yield (Kihara et al., 2012), while at a trial in Sadore, Niger, residues had no significant impact on yield (Abdou et al., 2012). At the Sadore trial, however, joint application of inorganic fertilizer and crop residue improved yields more than either alone, a result also seen at Saria, Burkina Faso (Abdou et al., 2012; Bationo et al., 2012b). At a trial in Kenya, crop residues increased soil C and soil aggregation (Kihara et al., 2012). At one of the trials where long-term manure improved soil pH, crop residue also increased soil pH from the baseline (Kibunja et al., 2012). As with supply constraints on manure, farmers in the Sahel likely do not have access to the amount of crop residues required. This is because residues are often also relied upon as cooking fuel, building material, and animal fodder (Buerkert and Hiernaux, 1998; Abdoulaye and Sanders, 2005). Based on the socio-economic constraints of organic input use as well as the benefits of joint inorganic and organic fertilizer applications, fertilizer and crop residue or manure should be applied together.

2.6.6 Crop rotation and intercropping

The diversification of cropping systems by incorporating legumes benefits crop production and soil fertility by adding biologically fixed N to the soil. Intercropping and rotation also may improve physical and chemical soil characteristics, such as soil water content (Fageria, 2009). At several long-term trials in West Africa, cereal-legume rotation and intercropping were higher yielding than continuous cropping (Bado et al., 2012; Bationo et al., 2012b). One trial in Kenya had similar yields between continuous maize and soybean-maize rotation, in which soybean did not receive the fertilizer N treatment that maize received, reducing N fertilizer requirements (Kihara et al., 2012). Intercrop and rotation may be more sustainable than continuous cereals, as mixed cropping systems declined in yield less than continuous cereal in other West African long-term trials (Bationo et al., 2012b). Adding legumes to cropping systems clearly benefits yield, however, research has shown mixed results for effect of legumes on soil properties. At a long-term trial in Guinea, West Africa, there was no difference in pH, exchangeable acidity, or concentration of N, Ca, or Al, between mixed cropping systems and continuous cereal (Bado et al., 2012). At a long-term site in Niger, the continuous cropping system was lower in OC (Adamou et al., 2007; Bado et al., 2012). Available P was lower in crop rotation than the continuous at two research sites, because of the higher P requirements of legumes (Knewtson et al., 2007; Bado et al., 2012). Rotation and intercrop was, however, found to have higher N and P use efficiencies than continuous cropping systems at two sites in Guinea and Niger (Adamou et al., 2007; Bado et al., 2012). Results from long-term research sites are inconclusive on whether cropping with legumes and cereals improves soil properties, however, intercropping and rotation is likely to improve yield sustainability and reduce external N fertilizer requirements.

Long-term soil fertility research in Sub-Saharan Africa has been invaluable for developing an understanding of the effect of the components of ISFM, including mineral fertilizer, crop residue, and manure application, and cropping with legumes, on soil properties and yield. The main focus of these trials has been on maximizing production and optimizing fertilizer rates and cropping systems. The issue of long-term sustainability has not received much attention. No trials have analyzed long-term yield trends under different management techniques, and few have considered the impact of several years of the practice on soil fertility and its relationship to sustainability. There is a need for research on the long-term effect of fertilizer microdosing and more research on the long-term effects of ISFM techniques to develop cropping systems that will secure livelihoods for both the current and future generations of Sahelian farmers.

3. LONG-TERM EFFECT OF FERTILIZER RATE ON SOIL PROPERTIES AND CARBON AND NITROGEN SPECIATION AT SADORE, NIGER.

3.1 Preface[1]

The impact of long-term fertilizer microdosing on soil fertility and soil organic matter dynamics is important to determine before it can be recommended as a sustainable soil fertility management practice for smallholder Sahelian farmers. A long-term research trial at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Sadore, Niger, established in 1993, was used in a study described in this chapter that compares a microdose (reduced) rate of fertilizer to the recommended application rate, and unfertilized soil. These long-term treatments provide opportunity to examine the effect of the microdosed fertilizer rate in the Sahel on crop yield trend, soil chemical properties and carbon and nitrogen speciation. As well, different rates of crop residue and manure applied along with the fertilizer treatments at Sadore allow the impact of organic matter application to be determined. This chapter covers the long-term effects of the microdosed rate of mineral fertilizer and the interaction of fertilizer application with organic amendments on yield trends, soil chemical properties, available nutrient levels and carbon and nitrogen speciation.

3.2 Abstract

Fertilizer microdosing, where farmers apply a reduced rate of fertilizer next to the seed within ten days of sowing, is a promising technique to address fertilizer use constraints faced by food insecure smallholder farmers in the Sahel of West Africa. Microdosing has shown yield improvements and increased nutrient use efficiency across the Sahel in the short-term; however, no long-term research on the effect of microdosing on soil fertility exists to determine the sustainability of the technique. The research described in this chapter assesses the impact of a reduced fertilizer rate of 15 kg N ha^{-1} and 4.4 kg P ha^{-1} on soil fertility compared to unfertilized

[1] Manuscript will be submitted to an academic journal (TBD) for publishing during thesis review process. Coauthors include D. Peak (provided financial assistance, laboratory facilities, ideas, feedback and manuscript editing), J.J. Schoenau (provided ideas, feedback and manuscript editing), A. Gillespie (help with SGM XANES analyses, data processing, and interpretation), G. Kar (significant lab assistance with soil property measurements), S. Koala (PI on INUWAM research project that this research contributes to, provided information on Sadore research site), B. Ouattara (PI on INUWAM project, provided information and involved in Saria research site), A. Kimaro (PI on INUWAM project), A. Bationo (initiated Sadore research site).

soil and a recommended rate of 30 kg N ha^{-1} and 13.2 kg P ha^{-1} added over sixteen years under continuous millet at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) site in Sadore, Niger. The interaction of fertilizer with crop residue and manure amendment at 300, 900, and 2700 kg ha^{-1} was also analyzed to determine ways to improve the sustainability of long-term mineral fertilizer application at a reduced rate. Yield trends and soil chemical properties including pH, cation exchange capacity (CEC), electrical conductivity (EC), total nitrogen (N) and phosphorus (P), and available P were determined as well as carbon (C) and N speciation using the X-ray Absorption Near Edge Structure (XANES) spectroscopic technique. Long-term application of a reduced fertilizer rate improved soil nutrient levels compared to unfertilized soil, while soil acidification, breakdown of organic matter, and the depletion of soil nutrients other than N and P were reduced compared to the recommended rate. Yield trends were negative for both the reduced and recommended fertilizer rates indicating mineral fertilizer alone is not sustainable over the long-term. Addition of crop residue or manure at 2700 kg ha^{-1} or greater along with fertilizer may better sustain long-term soil productivity. Organic amendments along with fertilizer buffered pH decline, provided additional nutrients, and increased the content of less humified and more labile organic C and N groups. Overall, application of a reduced fertilizer rate is an adequate alternative to the recommended rate for smallholders to manage soil fertility, working best with the concomitant application of all crop residue or manure available.

3.3 Introduction

Crop production is increasing at 1% per year across Sub-Saharan Africa (Chauvin et al., 2012), but is outpaced in the Sahel by a population growth rate of 3.1% (World Bank, 2014). Major reasons for low productivity increases include unstable rainfall patterns, low inherent soil fertility, low fertilizer use, and competition for organic inputs (Saïdou et al., 2004; Abdoulaye and Sanders, 2005). Fertilizer use is low in the Sahel because of high fertilizer cost, as well as limited access to fertilizer because of poor infrastructure and a weak private input sector (Saïdou et al., 2004; Abdoulaye and Sanders, 2005). Because of high fertilizer costs and uncertainty about production potential, it is often too risky for farmers to invest in applying the recommended rates of fertilizer to maximize yield (Aune and Bationo, 2008). Fertilizer microdosing, which is the application of about half the recommended rate of fertilizer next to the seed within ten days of sowing (Twomlow et al., 2008), has potential to ease smallholder fertilizer use constraints in the Sahel. Microdosing has been found in the short term to substantially increase yields and nutrient use efficiency, while reducing farmer investment and risk and increasing income (Buerkert and Hiernaux, 1998; Buerkert et al., 2001; Muehlig-Versen et al., 2003; Abdoulaye and Sanders, 2005; Tabo et al., 2007; Twomlow et al., 2008; Aune and Ousman, 2011; Bagayoko et al., 2011; Sime and Aune, 2014). While the short-term benefits of microdosing in the Sahel are known, there has been little research on the long-term effects of microdosing on soil fertility and agroecosystem sustainability.

There is some concern that microdosing may not be sustainable over the long term due to eventual soil nutrient depletion, especially without joint application of organic matter or return of crop residues (Buerkert et al., 2001; Muehlig-Versen et al., 2003; Aune and Bationo, 2008; Twomlow et al., 2008). Other research has indicated that microdosing improves long-term soil productivity compared to unfertilized soil through improving yield and biomass and increasing soil organic carbon (SOC), which is very important for soil functioning (Buerkert et al. 2001; Aune and Bationo, 2008; Bagayoko et al., 2011). No research, however, has been conducted to determine the effect of microdosing on SOC. Long-term research is essential to assess microdosing as a sustainable soil fertility management practice to meet smallholder nutrient requirements in the Sahel.

There is potential for the sustainability of microdosing to be improved with joint application of crop residue or manure. Understanding the interactions between microdosing and organic amendments like crop residue and manure is especially important because integrated soil fertility management (ISFM), which includes joint use of inorganic and organic fertilizers, has shown great potential for improving soil fertility and productivity in the Sahel (Vanlauwe et al., 2010; Gentile et al., 2013). For example, long-term application of manure in the Sahel has been found to sustain yields (Kihanda et al., 2012), improve SOC, and reduce acidification compared to fertilizer alone (Bado et al., 2012). At long-term research sites in the Sahel, crop residue amendment was shown to improve root growth, buffer against soil pH decline, and resulted in increased SOC and soil nutrient availability (Geiger et al., 1992; Buerkert and Hiernaux, 1998; Kihara et al., 2012; Kibunja et al., 2012). Addition of either crop residue or manure with fertilizer alters the soil C:N ratio, preventing nutrient losses by slowing the release of fertilizer N through immobilization, while at the same time speeding up the breakdown of organic inputs to increase humus formation (Fageria, 2009; Gentile et al., 2013; Rasche and Caddish, 2013). Unfortunately, crop residue and manure are both in low supply for smallholders (Buerkert and Hiernaux, 1998; Abdoulaye and Sanders, 2005; Bationo et al., 2012a). Research into the effects of different rates of organic matter inputs on soil along with fertilizer will improve our understanding of amounts that may be needed to provide sustainability benefits.

Measuring C and N content of soil is an important step in determining dynamics. However, going beyond measuring soil nutrient content by assessing the forms and nature of organic C and N in soil provides information on how nutrients and organic matter (OM) are cycling through the soil under different management practices. The X-ray Absorption Near-Edge Structure (XANES) technique can be used to measure C and N forms, or speciation in soil (Gillespie et al., 2014 a, b), and is a powerful technique that has not yet been utilized as a tool in Sahelian food security research. The forms of C and N that are in soil organic matter (SOM) reflect different points in the decomposition sequence from fresh plant material to polymerized humic materials (Wickings et al., 2012). The presence of C and N species found in plants indicates low microbial breakdown of organic inputs. Microbial-derived C and N groups indicate higher C and N breakdown and assimilation into microbial compounds and decomposition by-products (Gillespie et al., 2014a). Management practices such as fertilizer amendment, crop residue inputs, and tillage affect soil structure, soil pH, and microbial community composition, all of which influences SOM (Grandy and Neff, 2008; Wickings et al., 2012). Inherent soil properties such as mineralogy and texture are important long-term determinants of C and N speciation. Over the long term, SOM stabilization is dictated by access of microbes to substrate to break down C and N groups, and protection of OM from degradation through organo-mineral interactions (Lutzow et al., 2006; Schmidt et al., 2011). Using C and N XANES spectroscopy in the current research aids in understanding how long-term microdosing and organic amendment impact C and N dynamics.

The objective of this study is to determine the long-term effect of the microdosed rate of fertilizer on soil fertility and C and N dynamics, alone and in combination with crop residue and manure application. Our methods include analyzing yield trends, soil chemical properties, and C and N XANES spectra of soil from the Sadore long-term research site in Niger, West Africa. We hypothesize that the reduced rate will negatively affect soil fertility and nutrient cycling compared to the recommended rate, but that application of organic matter along with manure will reduce the negative effects of the microdosed rate.

3.4 Materials and Methods

3.4.1 Site description

The Sadore long-term research trial is managed by the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in southwestern Niger (Fig. 3.1). Annual precipitation at Sadore is 440-587 mm yr^{-1} and annual temperature is 28.3-28.9 °C. According to the World Reference Base (WRB) for soil resource classification system, the soil is a Hypoluvic Arenosol, which is an unstable sandy soil that is low in nutrient and water holding capacity and slightly enriched in clay in comparison to other Arenosol subgroups (Jones et al, 2013). Based on particle size analysis of the soil sand fraction in the control treatments of the Sadore trials, soil texture is 92.1% sand, mainly medium (40%) and fine sand (37.6%), with less coarse (15.8%), very fine (5.4%), and very coarse (1.2%) sand. The research plot was previously kept fallow for ten years and cropping began in 1993, with the first year of the trial beginning in 1994 (Akponikpe et al., 2008). The experiment was a 3^3 factorial RCBD layout with three replications per treatment (see Fig. A.1. for plot layout diagram). Treatments included varying rates of mineral fertilizer, crop residue, and farmyard manure under continuous *Pennisetum glaucum* (millet). The application rates for mineral fertilizer included a control of 0 kg N ha^{-1} and 0 kg P ha^{-1}, a reduced rate of 15 kg N ha^{-1} and 4.4 kg P ha^{-1}, which is equal to a microdosed rate, and a recommended rate of 30 kg N ha^{-1} and 13.2 kg P ha^{-1}. In the reduced and recommended treatments, N was applied as calcium ammonium nitrate (CAN), 10 days after sowing (DAS), 10 cm from the site of sowing and incorporated with a hand hoe. Phosphorus, applied as single super phosphate (SSP), was broadcast and ploughed into the soil before sowing for both rates of P (Akponikpe et al., 2008). Rates of crop residue and cattle manure amendment were each 300 kg ha^{-1}, 900 kg ha^{-1}, and 2700 kg ha^{-1} dry weight. Average manure nutrient contents were 1 ± 0.05 % N, 0.2 ± 0.01% P and 1.6 ± 0.09% K (mean ± SD) and average crop residue contents (weighted leaf and stem content) were, 0.74 ± 0.14 % N, 0.05 ± 0.01% P and 2.54 ± 0.44% K (Akponikpe et al., 2008). Crop residue was broadcast as surface mulch and manure was broadcast and incorporated, both applied before sowing. There was no control treatment for organic amendments because there are some organic inputs even in traditional low input systems; some residue is left in the field after gathering for other uses, and passing grazing animals will still deposit manure in the field (Akponikpe et al., 2008). Sowing took place after the first rain, which was most commonly in June, but in some years took place in earlier May or in July, with delayed rains. Millet was planted at 10000 hills ha^{-1} and after two to three weeks thinned to 30000 plants ha^{-1}. Hand weeding took place two to three times per cropping season to control weeds.

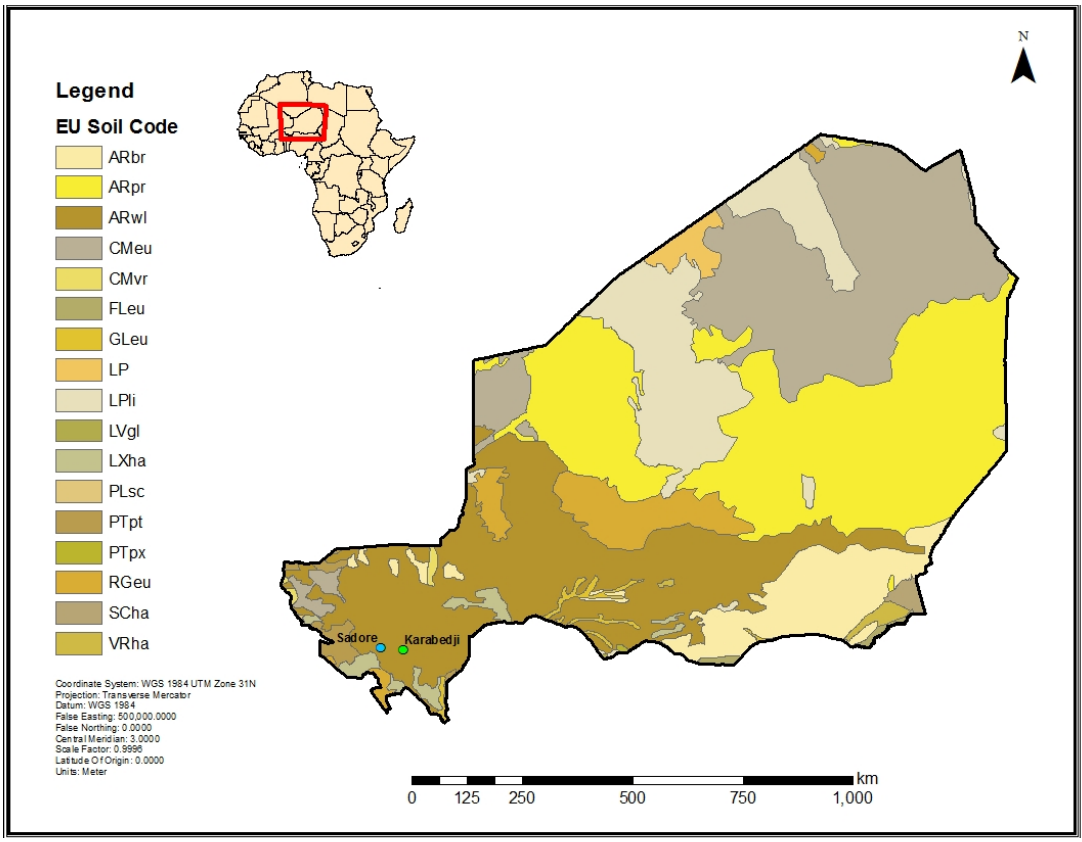


Fig. 3.1. Soil map of Niger with location of Sadore long-term agronomic research site. Sadore site is ARwl, Hypoluvic Arenosol (Adapted from Jones et al., 2013).

3.4.2 Soil sampling and chemical analyses

This research project began after soils were already sampled and sent to the University of Saskatchewan, thus I did not make first-hand observations and cannot completely ensure the type of quality control practices put in place during soil sampling. I was able to, however, communicate in person and by email with researchers involved at the sites to understand sampling, research design, and history of the plots. Soil samples were collected prior to sowing in June 2013; three composited and well-mixed samples were taken from each plot at the 0-20 cm depth using an auger. A sub-sample was taken from the composite sample, air-dried, ground to pass through a 2 mm sieve, packaged in individual airtight sealed bags, and shipped to researchers at the University of Saskatchewan in August 2013. After receipt of soils from Niger, soil samples were stored in air-tight vials and analyzed from September 2013 to July 2014 for pH, electro-conductivity (EC), organic carbon (OC), total phosphorus (P) and nitrogen (N), available P, and effective cation exchange capacity (CEC). Both EC and pH were measured in triplicate using a glass electrode in a 2:1 water:soil suspension, with 10 mL of water and 5 g of soil (Carter and Gregorich, 2008). The LECO-C632 carbon determinator (LECO© Corporation, 1987) was used to analyze two 0.3 g replicates of each soil sample for OC concentration. Low carbon standard reference materials were used for calibration, and a quality control sample of known OC content was measured every 20 analyses. Total N and P were measured in triplicate according to the acid block digestion method of Thomas et al. (1967). Digests were then allowed to cool to room temperature, diluted and analyzed on an auto-analyzer. A standard soil of known concentration of N and P respectively was used for quality control. Available P and CEC were determined using a Mehlich-3 extraction, as described by Carter and Gregorich (2008). The Mehlich-3 extraction was chosen because of its ability to extract multiple elements of interest to this study, and its applicability to tropical acidic soils (Carter and Gregorich, 2008). Available P was determined from the Mehlich-3 extracted soil solution using an auto-analyzer and CEC was calculated by measuring the concentrations of exchangeable Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} cations in vacuum filtered Mehlich-3 solutions on the Microwave Plasma Atomic Absorption Spectrometer (MP-AES 4100, Agilent Technologies). CEC was then determined as the sum of exchangeable base cations. The concentrations of Al^{3+} and H^{+}, which would also contribute to CEC, were not determined because there was not enough soil from each treatment to complete these analyses, which require a large amount of soil.

3.4.3 X-ray absorption spectroscopy

Carbon and nitrogen speciation was determined by measuring X-ray Absorption Near Edge Structure (XANES) at the C and N *K*-edges at the Spherical Grating Monochromator

(SGM) beamline 11ID-1 at the Canadian Light Source in Saskatoon, Saskatchewan, Canada. At the C and N *K*-edges, the beam line delivers 10^{11} photons s^{-1} with a resolving power of (E/ΔE) >10,000 (Regier et al., 2007a, b). The energy range for the C *K* -edge is from 270 to 320 eV, and the N XANES *K*-edge is between 380 and 430 eV. Samples were prepared by slurrying a small amount of the soil sample with water, pipetting onto Au-coated Si wafers attached to the sample holder using double-sided carbon tape, and allowing to air dry. The rep for each treatment highest in OC% was selected for XANES measurement to reduce instrument noise because all soil samples were low in C. Soil OC and total N contents, and C:N ratio of samples selected for XANES analysis are all in Table A.1 of Appendix A. After sample preparation, samples were loaded into the SGM end station and brought under vacuum. Data was collected for the C and N *K*-edges separately using the slew scanning mode, in which the monochromator scans the energy range of each element, acquiring data while minimizing X-ray exposure to sample (Gillespie et al., 2015). An average of 60 scans were taken per sample at a new spot on the sample for each scan to avoid radiation damage. The beam line exit slit was set to 25 μm and partial fluorescence yield was collected using one Amptek silicon drift detector. XANES spectral features for C and N types were identified from diagnostic peaks, which have been previously identified from analysis of reference compounds (Leinweber et al., 2010; Myneni, 2002; Urquhart and Ade, 2002). Citric acid was used for calibration at the C *K*-edge where the peak at 288.8 eV was used for energy calibration. Normalization to incident flux (I_0) was carried out by recording the scattering intensity from a freshly sputtered (carbon free) Au surface across the C *K*-edge (Gillespie et al., 2015). The N *K*-edge data was calibrated to the υ=0 vibration of interstitial N_2 gas (at 400.8 eV) in solid-state ammonium sulfate (Gillespie et al., 2008).

3.4.4 Data analyses

Grain yield data, which was provided to researchers for each year of the trial, was analyzed using PROC MIXED in SAS (Version 9.4; SAS Institute, Cary, NC) to calculate the regression of yield (y) on time (x). This analysis was conducted to assess the ability of the different fertilizer treatments to sustain yield over time. Mean comparisons of soil properties were also conducted with PROC MIXED in SAS. See Tables A.2. to A.8. in Appendix A for ANOVA results. The Tukey-Kramer test method of multi-treatment comparison for least significant differences (LSD) was used for mean comparison, with treatments as fixed effect and replications as block effect. Significance for yield regression and soil property mean comparison was declared at $p \le 0.05$. Normality was tested for each yield parameter and soil chemical property. C and N XANES data was processed using IGOR Pro v.6 software (Wavemetrics, Lake Oswego, Oregon USA).

3.5 Results

3.5.1 Yield trends over time

Regressions of millet grain yield versus time were calculated for each fertilizer rate strategy at low, medium, and high manure and crop residue rates, collectively called OM rates, in the continuous system (Table 3.1), and the yield trend over time was graphed (Fig. 3.2). Average millet crop yield was lowest for the control treatment with low OM, at 184 kg ha^{-1} and was highest for the recommended fertilizer rate with high OM, at 1094 kg ha^{-1}. As well, average yield was higher for the reduced fertilizer rate with high OM, at 1062 kg ha^{-1}, than the recommended fertilizer rate with low OM, which was 862 kg ha^{-1}. The increase in yield above the control (unfertilized) treatment was greatest for the recommended rate, especially in the early years, with a 110% increase from the control to reduced fertilizer rate treatment, and a further 16% increase between the reduced and recommended rate treatments. There is no significant relationship between yield and time for the control fertilizer treatment, but there is a negative relationship between yield and time for the reduced and recommended fertilizer rate treatments for each OM rate (Table 3.1). The strongest negative relationship between yield and time, where R^2 was highest, was the recommended fertilizer rate treatment at the low OM rate, explaining about 52% of the variation in yield ($p<0.01$), whereas all other treatments for yield trends explain between 32% ($p<0.05$) and 40% ($p<0.01$) of variation. The reduced fertilizer and medium OM rate has the lowest R^2 value at 0.32. Although the negative trend in Fig 3.2 is significant, less than 40% of yield variation is explained in the model. Regressions of precipitation and variability of precipitation on time and yield were not significant, indicating a precipitation decline or increase in variability of precipitation does not explain the negative yield trend. Specific drought events, which occured in Niger in 2005, 2010, and 2012, may have affected crop production in those and subsequent years, however.

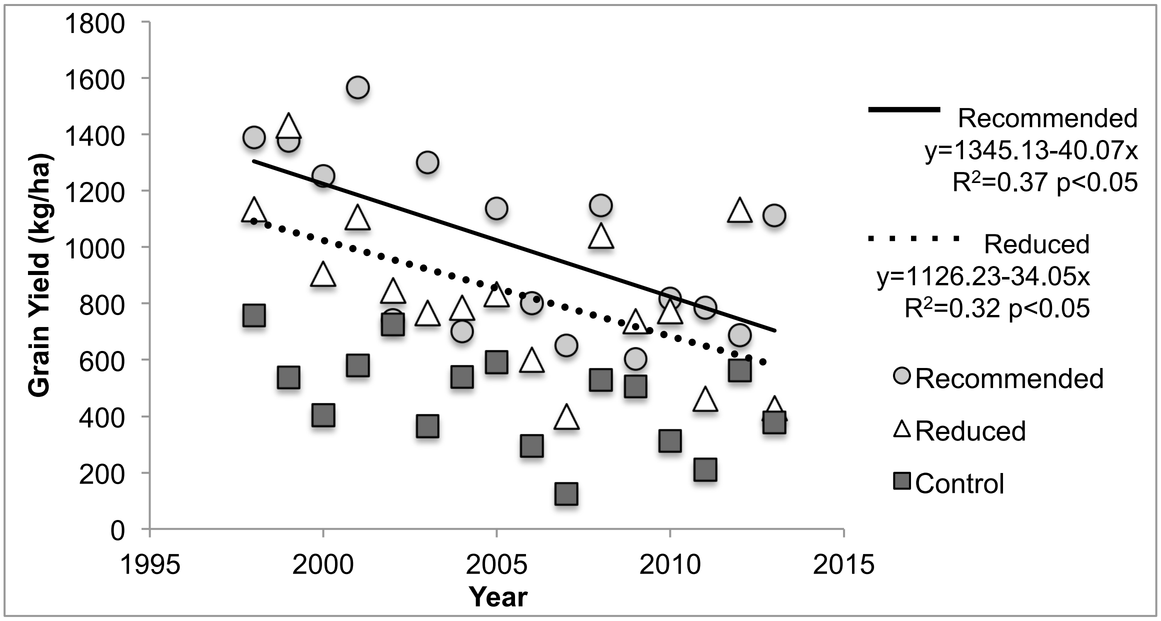


Fig. 3.2. Regression of millet yield versus time (year) for each fertilization strategy at Sadore site from 1998 to 2013 in the continuous millet system. Regression lines only exist for recommended and reduced fertilizer treatments, as there was no significant regression for the control.

Table 3.1. Regression of millet yield versus time in the different fertilizer and organic matter rate treatments over 16 years (1998-2013) at Sadore site **in the continuous millet system.**

Fertilizer Rate	Crop Residue and Manure Rate	Mean Yield kg ha^{-1}	Equation	R^2	
Control†	Low‡	184	y=246.63-7.3162x	0.0804	ns
	Medium	464	y=615.38-17.86x	0.2346	ns
	High	567	y=706.20-16.37x	0.138	ns
Reduced	Low	656	y=1012.93-41.95x	0.3746	*
	Medium	837	y=1126.23-34.05x	0.3217	*
	High	1062	y=1423.63-42.50x	0.3968	**
Recommended	Low	862	y=1196.2-39.34x	0.517	**
	Medium	1005	y=1345.13-40.07x	0.3704	*
	High	1094	y=1455.03-42.41x	0.343	*

†Control, reduced and recommended rate correspond to 0 kg ha^{-1} N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer.

‡Low, medium, and high crop residue and manure rates correspond to 300, 900, and 2700 kg ha^{-1} each for crop residue and manure added per year for 16 years.

*significant at $p<0.05$; **significant at $p<0.01$

3.5.2 Effect of fertilizer rate on soil chemical properties and interaction with organic amendments

Increased fertilizer rate significantly decreased soil pH at Sadore from 5.3 without fertilizer to 5.0 at the recommended rate (Table 3.2). Fertilizer rate had no effect on EC or CEC (Table 3.2), and crop residue and manure also did not interact with fertilizer to impact EC or CEC. CEC measurements are below 2.6 $cmol_c\ kg^{-1}$ and thus considered very low for all treatments (Metson, 1961). Note also that effective CEC does not include exchangeable acidity and thus does not reflect the total amount of exchange sites in soil. EC is well below 4 $mS\ cm^{-1}$, thus soils are far from saline.

Manure did not interact with fertilizer to impact pH, but crop residue (CR) and fertilizer application did interact to buffer soil pH decline (Table 3.3). Increasing the CR rate at the control and reduced fertilizer rates resulted in an increase in pH from 5.2 to 5.5 in the control fertilizer treatment and from 4.9 to 5.2 at the reduced fertilizer rate. There was no significant effect of crop residue rates at the recommended fertilizer rate.

Table 3.2. Soil chemical properties by fertilizer rate in the surface (0-20 cm) soil at Sadore site.

Fertilizer	pH	EC	CEC
		$mS\ cm^{-1}$	$cmol_c\ kg^{-1}$
Control†	5.3a‡	0.048a	0.7a
Reduced	5.1b	0.053a	0.6a
Recommended	5.0c	0.052a	0.6a

†Control, Reduced and Recommended rate correspond to 0 $kg\ ha^{-1}$ N and 0 $kg\ ha^{-1}$ P, 15 $kg\ ha^{-1}$ N and 4.4 $kg\ ha^{-1}$ P, and 30 $kg\ ha^{-1}$ N and 13.2 $kg\ ha^{-1}$ P respectively applied per year for 16 years as CAN and SSP fertilizer. Crop residue and manure rates are averaged for each fertilizer rate.

‡Means within a column followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

Table 3.3. Effect of fertilizer and crop residue treatments on soil pH (1:2 soil:water extract) in the surface (0-20 cm) soil at Sadore site.

Fertilizer	Crop Residue	pH
Control†	Low‡	5.2bc§
	Medium	5.3b
	High	5.5a
Reduced	Low	4.9de
	Medium	5.1cd
	High	5.2bc
Recommended	Low	4.9e
	Medium	5.0de
	High	5.0de

†Control, Reduced and Recommended rate correspond to 0 kg ha^{-1} N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer.
‡Low, medium, and high crop residue rates correspond to 300, 900, and 2700 kg ha^{-1} crop residue added per year for 16 years. Manure rate is averaged for each combination of crop residue and fertilizer.
§ Means followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

3.5.3 Effect of fertilizer rate on soil N, P, and OC, and interaction with organic amendments

Total and available P and total N concentration in the 0-20 cm depth of soil increased with fertilizer rate under amendment treatments of both manure and crop residue (Tables 3.4 and 3.5). As well, fertilizer and manure rates interacted to significantly affect soil N and P (Table 3.4). The high manure rate treatment had the highest total P concentration, with no significant difference among fertilizer rates at this manure rate. At the low and medium manure rates, however, both increased fertilizer and manure rates increased total P. Fertilizer had a greater influence on available P and total N than manure. At the recommended rate of fertilizer, available P was higher in the low rate than in the high rate treatment of manure. Also, unexpectedly for total N, the low manure rate at each fertilizer rate was higher than the other manure rates, indicating that increased manure is having a slightly negative effect on soil N content.

Table 3.4. Effect of fertilizer and manure treatment on soil total and available P and total N in the surface (0-20 cm) soil at Sadore site.

		Total P	Available P	Total N
Fertilizer	Manure	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Control†	Low‡	116.2f§	4.2e	111.6bc
	Medium	142.7de	6.7de	95.9cde
	High	173.4abc	6.7de	80.6e
Reduced	Low	127.2ef	9.2de	120.7b
	Medium	166.6bc	10.7cde	97.9cd
	High	191.7a	12.7cd	80.6e
Recommended	Low	152.0cd	30.8a	138.3a
	Medium	180.0ab	17.5bc	118.7b
	High	186.8ab	20.4b	124.1ab

†Control, reduced and recommended rate correspond to 0 kg N ha^{-1} and 0 kg P ha^{-1}, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied every years for 16 years as CAN and SSP fertilizer.
‡Low, medium, and high manure rates correspond to 300, 900, and 2700 kg ha^{-1} crop residue added per year for 16 years. Crop residue rate is averaged for each combination of manure and fertilizer.
§ Means followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

Crop residue and fertilizer application both contribute to improved total P content of the soil at Sadore (Table 3.5). Total P was highest with the recommended fertilizer and high rate of crop residue and decreased with decreasing fertilizer and crop residue application rates. Differences in total P between crop residue rates were significant at the recommended fertilizer rate, but there was no significant difference in total P between crop residue rates in the reduced or control fertilizer treatments.

Table 3.5. Effect of fertilizer and crop residue treatment on soil total P in the surface (0-20 cm depth) soil at Sadore site.

		Total P
Fertilizer rate	Crop Residue rate	mg kg^{-1}
Control†	Low‡	148.6cd§
	Medium	135.4d
	High	148.2cd
Reduced	Low	149.0cd
	Medium	168.6abc
	High	167.9abc
Recommended	Low	159.5bc
	Medium	174.2ab
	High	185.1a

†Control, Reduced and Recommended rate correspond to 0 kg ha^{-1} N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer.
‡Low, medium, and high crop residue rates correspond to 300, 900, and 2700 kg ha^{-1} crop residue added per year for 16 years. Manure rate is averaged for each combination of crop residue and fertilizer.
§Means followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

The fertilizer treatments had little impact on soil OC at the Sadore site, and OC was very low overall (Table 3.6). The history of fertilizer addition resulted in a slight but significant increase in soil organic carbon content in the fertilized treatments of 0.03% compared to the control. There was no significant interaction between fertilizer and manure or fertilizer and crop residue. Fertilizer, crop residue, and manure did jointly interact to impact OC, however (Table A.9). OC was very similar for most treatments, but generally higher with higher rates of all inputs, and lower with lower rates of all inputs, ranging from 0.20% OC to 0.31% OC.

Table 3.6. Soil organic carbon in the surface (0-20 cm) soil as affected by fertilizer rate at Sadore site.

Fertilizer Rate	Organic Carbon
	%
Control†	0.24b‡
Reduced	0.26a
Recommended	0.27a

†Control, reduced and recommended rate correspond to 0 kg ha- N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer. Crop residue and manure rates are averaged for each fertilizer rate.
‡Means followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

3.5.4 Effect of fertilizer, manure and crop residue rate on C and N XANES spectroscopy

The results from the C XANES analysis of treatments at Sadore (Fig. 3.3) show differences between treatments in aromatics (peak 1), carboxyls (peak 4), and carbohydrates, (peak 5), with minimal differences in ketones (peak 2) and phenols (peak 3). The treatment with high rate of fertilizer, manure, and crop residue (R2F2M2) is highest in aromatics and both the control OM and reduced fertilizer (R0F1M0) and high OM with control fertilizer (R2F0M2) treatments were lowest. Abundance of both organic and mineral fertilizer inputs appears to be a dominant controller of aromatic abundance. Treatments with lower fertilizer rates, regardless of OM rate, were higher in carboxyl groups. The control treatment (R0F0M0) was highest in carboxyl, followed by high OM amendment with no fertilizer (R2F0M2) and control OM amendment with reduced fertilizer rate (R0F1M0). R2F2M2, R2F1M2, and R0F2M0 were lower in carboxyls, and had the highest mineral fertilizer inputs. Carbohydrates were highest in the control OM and recommended fertilizer treatment (R0F2M0), where organic inputs were lowest and fertilizer highest. Carbohydrate abundance was more related to organic matter abundance relative to mineral fertilizer, whereas aromatics were more related to overall fertility inputs, and carboxyls were related to mineral fertilizer inputs.

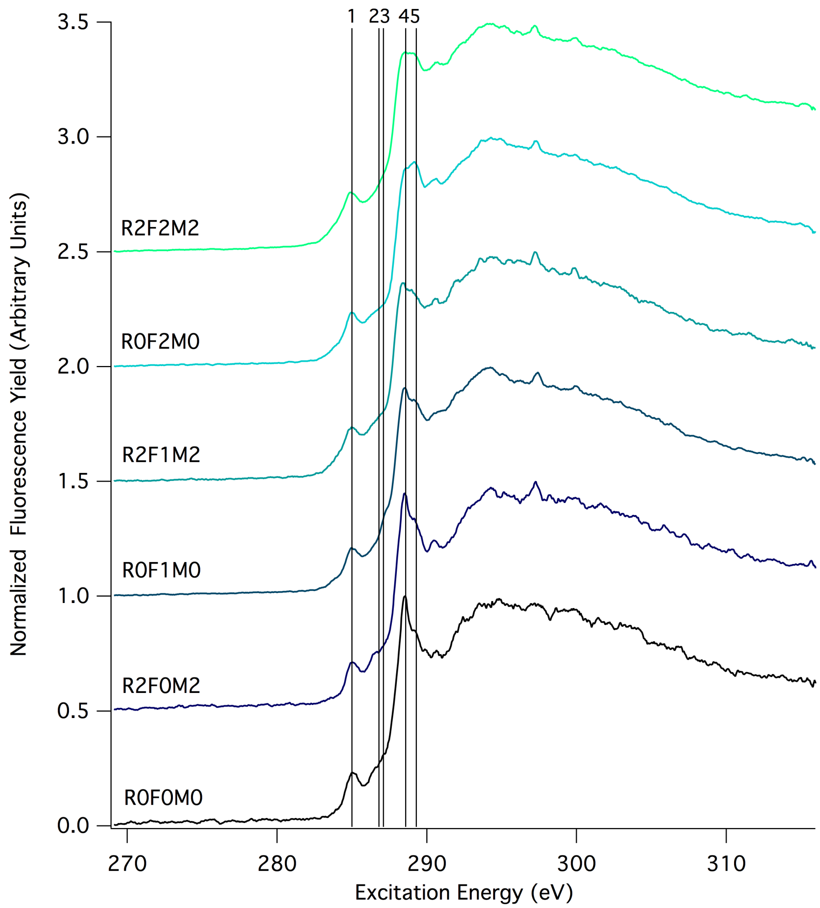


Fig. 3.3. Normalized fluorescence yield of C K-edge XANES spectra of soils at Sadore by fertilizer treatment in combination with varying organic amendment rates. R=residue, F=fertilizer, M=manure; F0=control, F1=reduced rate, F2=recommended rate; R0 and M0= 300 kg ha- rate, R1 and M1= 900 kg ha- rate, R2 and M2= 2700 kg ha- rate. Carbon features corresponding to specific excitation energy are identified as: 1. aromatic-C at 285 eV; 2. ketones at 286.8 eV; 3. phenolic at 287.1 eV; 4. carboxylic at 288.6 eV; 5. carbohydrate hydroxyl at 289.6 eV.

The N XANES spectra for each fertilizer and amendment treatment at the Sadore site are shown in Fig. 3.4. The largest difference between treatments is in the height of the amide peak: peak 2. Treatments with the highest organic matter (OM) inputs added as crop residue and manure with the control and reduced fertilizer rates (R2F1M2 and R2F0M2) were highest in amides. The control (R0F0M0) and highest amendment intensity (R2F2M2) treatment were moderate in amides, and the treatments lowest in amides were those with low OM rates and fertilizer applied at either rate (R0F1M0 and R0F2M0). The rate of organic inputs compared to fertilizer seems to have an impact on amide abundance. The control treatment and treatments with high OM additions (R2F1M2, R2F0M2, R2F2M2, R0F0M0) that were high and moderate in amides were highest in pyrrolics (peak 3). Treatments with fertilizer application and no OM amendment (R0F1M0 and R0F2M0) that were lowest in amides were also lowest in pyrrolics. There was no difference between treatments for peak 1 (pyridine and pyrazines), or peak 4 (N-bonded aromatics). The control fertilizer and high OM treatment (R2F0M2), which is abundant in amides and pyrrolics, is lower in alkyl-N, peak 5, compared to all other treatments, indicating alkyl-N may build up as amides and pyrrolics break down. The alkyl-N peak for R2F0M2 is also shifted to the left, along with R2F1M2, although R2F1M2 is not depleted at the alkyl-N peak compared to the rest of the treatments. These treatments were both highest in amides.

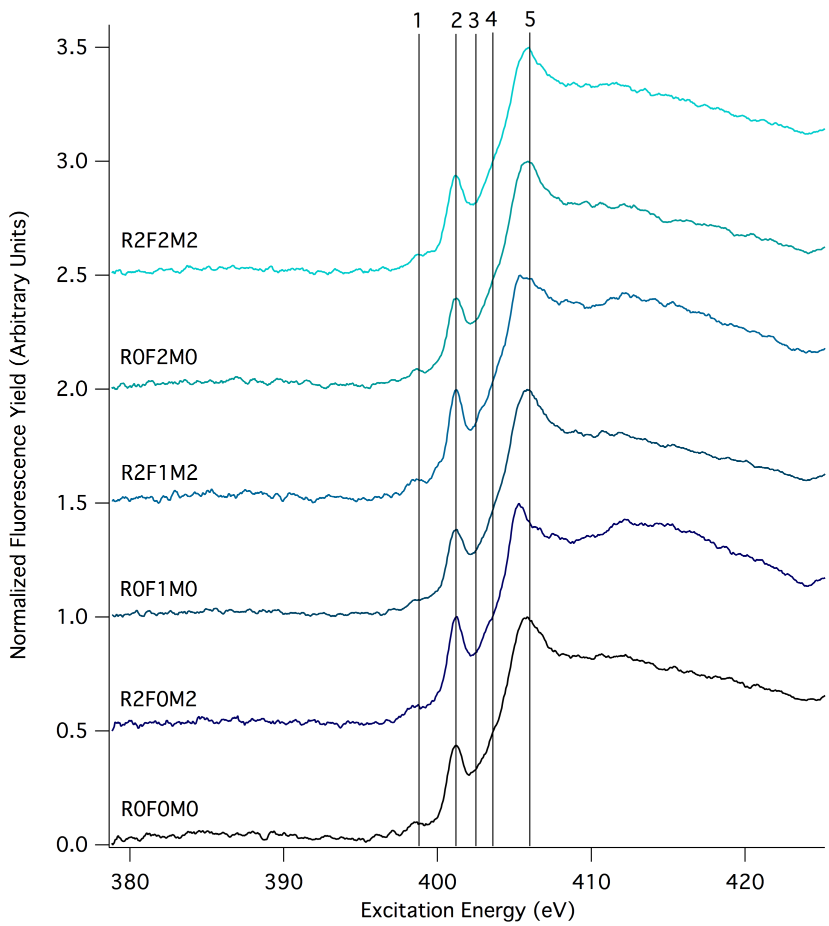


Fig. 3.4. Normalized fluorescence yield of N K-edge XANES spectra of soils at Sadore by fertilizer treatment in combination with varying intensities of organic amendments. Abbreviations of soil treatments are same as for Fig. 3.3. Nitrogen features corresponding to specific excitation energy are identified as: 1. pyridines and pyrazines, aromatic N in 6-membered rings at 398.8 eV; 2. amide at 401.2 eV; 3. pyrrolic, N in 5-membered rings with unpaired electrons, at 402.5 eV; 4. N-bonded aromatics at 403.5-403.8 eV; 5. alkyl-N at 406 eV.

3.6 Discussion

3.6.1 Yield average and trends

Based on the yield results, fertilizer greatly improved yield in the initial years of application, but yield trend was negative with fertilizer application over time at Sadore. Yield was highest with the recommended fertilizer rate, but relative to amount of fertilizer applied, the yield response per unit of fertilizer applied was greater for the reduced rate than the recommended rate. Similar yield response was seen in short-term microdosing trials in Africa, ranging from 46% to 113% depending on the fertilizer rates, cereal crops grown, and climatic conditions under which the specific trial was conducted (Buerkert et al., 2001, 2002; Muehlig-Versen et al., 2003; Aune and Ousman et al., 2011; Bagayoko et al., 2011). Yield benefits from fertilizer use has been reported in other long-term studies in the Sahel region (Abdou et al., 2012; Bationo et al., 2012b), however, many Sahel studies also report declining yield over time with long-term fertilizer application (Bado et al., 2012; Bationo et al., 2012b; Kibunja et al., 2012). As mentioned previously, the regression model is significant but time explains less than 40% of variation in yield. Yield variations may also be due to drought or pests. Some of the yield decline over time may be due to weed and disease accumulation due to lack of rotation. Soil factors that may have a hand in yield decline can be elucidated from the following soil fertility and OM cycling results. The main lesson from the yield results at Sadore are that fertilizer is important for yield improvement but that for both the reduced and recommended fertilizer treatments, yield trend is negative and thus one is not sustaining yield better than the other,

3.6.2 Soil chemical properties

Long-term nitrogen fertilizer application at Sadore led to a decrease in soil pH, which may be contributing to the observed negative yield trend. A soil pH decrease of similar magnitude with nitrogen fertilizer application, attributed to acidity produced in the nitrification of ammonium to nitrate, has been noted in other long-term temperate and tropical research (Bado et al., 2012; Caires et al., 2015; Divito et al., 2011; Kibunja et al., 2012; Manna et al., 2005; Williams et al., 2014). The decrease in pH at Sadore of 0.3 pH units is not large but may slightly decrease availability of Ca^{2+}, Mg^{2+}, K^{+}, and S as these nutrients decrease in abundance from pH 5.5 to 5.0 (Truog, 1947). The reduced rate of fertilizer causes less soil acidification than the recommended and thus may be less detrimental to soil productivity over the long-term.

Soil acidification may be further prevented through organic matter amendment. Both crop residue and manure add base cations to the soil that neutralize acidity through cation exchange, and add organic matter that neutralizes acidity through ammonification, decarboxylation, and reaction of H^+ with organic anions (Haynes and Mokolobate, 2001; Butterly et al., 2013; Cai et al., 2014). Crop residue buffered soil against pH decrease at Sadore, which is consistent with other Sahelian research (Kretzschmar et al., 1991; Geiger et al., 1992), although only in the control and reduced fertilizer treatments. This suggests the recommended fertilizer rate produces more acidity than the current crop residue rates can buffer. Manure did not improve pH at Sadore, and higher rates may be necessary. In other research where rates were 5000 kg ha^{-1} or higher, manure buffered acidity from N fertilizer application (de Ridder and Van Keulen, 1990; Manna et al., 2005; Cai et al., 2014). Crop residue and manure applied at higher rates than at Sadore (2700 kg ha^{-1}) may thus be required to stabilize soil pH and yields.

Cation exchange capacity (CEC) is very low at Sadore, and neither fertilizer nor organic matter application had an impact on CEC. This is likely because both soil pH and OC, properties that have a direct relationship with soil CEC, are low at Sadore and treatment effects on these properties were not large. Higher rates of organic matter are likely necessary to improve CEC, as other Sahel research did show an increase in CEC with pH increase from crop residue application (Geiger et al., 1992). CEC is more closely related to SOC content in millet cropland in the Sahel than it is to soil clay content or mineralogy (Manu et al., 1991; Bationo et al., 2007).

3.6.3 Soil nutrient content

Along with soil acidification, yield decline may also be due to depletion of S, K, or micronutrients that are not added to the soil with the N and P fertilizer treatments. An initial examination of the N, P and K balances at the Sadore long-term site calculated a positive balance for N and P in all treatments but a negative K balance at the recommended fertilizer rate with the low and medium crop residue and manure rates because of higher yield and nutrient removal (Akponikpe et al., 2008). The negative K balance in these treatments at Sadore has likely increased over time since the 2008 study and may be contributing to yield decline. A similar negative yield trend occurred at several long-term trials in India where N, P, and K rates were imbalanced, and thus nutrients were deficient (Srivastava et al., 2002; Manna et al., 2005). The reduced rate, even without organic matter application, would result in a smaller depletion of K and other nutrients than did the recommended rate.

Yield declines over time from loss of K and other nutrients not added in fertilizer may have been minimized by addition of manure with N and P, because manure contains micronutrients and base cations (Srivastava et al., 2002; Chaudhary and Narwal et al., 2005) that may have provided a yield benefit at Sadore when N and P were not limiting. This is consistent with the observation that total N content, for every fertilizer rate, and available P content, at just the high fertilizer rate were highest when manure rate was lowest. Higher manure rates increased crop yields, leading to greater total N and available P removal from the soil. Both reducing fertilizer rate and adding manure may improve content of soil nutrients not added with fertilizer, which may reduce yield decline over time. Soil N may also be lower with a higher manure rate because manure may stimulate organic N decomposition. One laboratory study found that manure application increased nitrate production due to stimulation of microbial activity, which could lead to increased N losses through leaching (Müller et al., 2003). This explanation does not account for lower available P; however, with either explanation manure and crop residue are not improving total N and available P thus fertilizer application is needed to maintain these nutrients.

Overall, fertilizer application is essential to maintain soil N and P for crop production in the Sahel, and the reduced rate helps to maintain N and P levels and reduces depletion of other nutrients. It does come at the expense of reduced yield in the initial years of fertilizer addition. Increase in available P (Geiger et al., 1992; Buerkert et al., 2000; Sinaj et al., 2001; Yamoah et al., 2002) and total N and P (Van der Eijk et al., 2006; Williams et al., 2013) with fertilizer application is also reported in other long-term research both in the Sahel and globally. Available N as nitrate is not considered in the current study because amounts were very low and nitrate does not typically accumulate in tropical soils.

Both crop residue and manure improved total P with fertilizer application, but only manure impacted available P levels. Crop residue improved total P especially at lower fertilizer rates, where there was little difference between residue rates. This may be because any P in residues is being mineralized to meet plant P demand through production of extracellular phosphatase enzymes (Reddy et al., 2000). A similar demand-induced solubilization of crop residue P was reported in other Sahel research (Hafner et al., 1993). Crop residue did not impact available P with fertilizer application in other West African trials (Yamoah et al., 2002; Michels and Bielders, 2005; Knewston et al., 2008). This is likely because unlike manures, crop residue decomposition does not supply as much organic acids to chelate with P sorbing Fe and Al oxides and mineral surfaces and release P to the soil solution (Hue et al., 1991; Manu et al., 1991; Braos et al., 2015). Manure would further improve available P if application rates were high enough to increase pH (Kihanda et al., 2012), which reduces chelation of P to mineral surfaces and metal oxides and improves bioavailability in acidic soils (Sharpley and Moyer, 2000; Braos et al., 2015). Manure amendment increases total P in soils partly because cattle manures have low N:P ratios and can add considerable amounts of both total and labile P to soils (Kar, 2013). As well, addition of C in manure may increase total P retention because OC content is highly correlated to total P in millet cropping soils of the Sahel (Manu et al., 1991). Build up of residual P with manure application may lead to increased total P over time (Kashem et al., 2004), as was observed in a long-term trial in Kenya (Janssen et al., 2008; Kihanda et al., 2012). Addition of manure can increase residual P stores by stimulating microbial activity leading to conversion of inorganic P to organic P (Reddy et al., 2000). At the medium and low manure rates, the amount of P added in manure may not be enough to build up substantial residual P because the residence time of the residual pool is based on the amount of labile P applied (Wolf et al., 1987). In summary, total P build up with fertilizer use is further increased with both crop residue and manure application, but only manure application at high rates improves P availability.

3.6.4 Soil organic carbon

Soil organic carbon was very low overall, and although application of fertilizer at either the reduced or recommended rate significantly increased OC compared to the control, it was only by 0.02-0.03%. The slight OC increase with fertilizer is due to improved yield and biomass production (Alvarez et al., 2005). SOC may not increase with fertilizer addition because fertilizer N is stimulating organic matter degradation (Chivenge et al., 2010). Although C is low, it is not declining, because SOC measured in the top 20 cm of the soil at the start of the experiment was 0.18% C, which is similar to current SOC levels (Akponikpe et al., 2008). Thus, SOC decline, which has explained yield decline in other long-term field research (Manna et al., 2005), does not explain yield decline at Sadore in comparison to changes in soil acidification and nutrient deficiency.

SOC also did not improve substantially with crop residue or manure application. These results for fertilizer and organic amendment are similar to several other long-term trials in the Sahel, where SOC declined over time (Yamoah et al., 2002; Janssen, 2011; Fonte et al., 2009; Bationo et al., 2012b; Kibunja et al., 2012). Difficulty in sequestering OC in other Sub-Saharan African long-term trials was attributed to rapid mineralization and soil erosion from the arid climate and to continuous cultivation and a lack of OM protection in sandy Sahel soil (Kapkiyai et al., 1998; Yamoah et al., 2002; Janssen, 2011; Eche et al., 2013). Trials that were successful in accumulating OC in West Africa were higher in clay content, which increased aggregation and protected SOM from decomposition (Feller and Beare, 1997; Gentile et al., 2013). SOC was also increased in the Sahel where manure rates were two to three times higher than this study (Nakamura et al., 2012); these rates may not be feasible for smallholder farmers, however. Crop residue did not prevent SOC decline in any Sahel research, as the high C:N of residues slowed their breakdown and contribution to SOC (Kapkiyai et al.,1998; Ouédraogo et al., 2007). While manure, crop residue, and fertilizer have minimal effects on soil carbon content, studying the soil C and N speciation should shed light on how the treatments are affecting SOM storage and C and N dynamics.

3.6.5 C and N speciation

Two components most influenced C and N speciation at Sadore: 1) rates of organic and inorganic inputs and their comparative amounts; and 2) the sandy soil texture at Sadore, which decreased the retention of certain C and N groups, because coarser soil retains mostly plant derived SOM that is rapidly depleted when conditions favor mineralization (Feller and Beare, 1997; Grandy et al., 2008; Grandy and Neff, 2008; Gillespie et al., 2014a). C and N groups produced through microbial degradation are retained in the fine mineral fraction where they are protected from breakdown (Grandy and Neff, 2008). The mineral fraction is a very small portion of soil particles at Sadore, thus these groups were not retained in the soil to any large extent. Both soil texture and fertilizer inputs played a role in the relative abundance of C and N functional groups in the soil.

The N functional groups varying in abundance between treatments are amide-, pyrrolic- and alkyl-N at Sadore. Amide- and pyrrolic-N were both abundant and alkyl-N was lowest where organic amendment was highest and inorganic fertilizer was reduced or absent. Pyrrolics were also present in similar abundance when organic matter and fertilizer were applied at similar rates, however. Both amides and pyrrolics were lowest where there was more fertilizer and less organic matter inputs, indicating that a higher amount of inorganic N fertilizer compared to OM addition stimulates their break down. Pyrrolics are heterocyclic plant compounds formed through reaction of inorganic N with humic and fulvic acid compounds and they generally increase with degree of humification (Thorn and Mikita, 1992; Mengel et al., 1996; Mahieu et al., 2000; Vairavamurthy and Wang, 2002). Heterocyclic N compounds are produced earlier in the OM decomposition pathway and they persist throughout breakdown (Vairavamurthy and Wang, 2002), which is likely why pyrrolics are abundant in more treatments than amides. In contrast with this study, at a long-term maize trial in Ontario, where only the fine-fraction was measured, heterocyclic N was most abundant in treatments with a lower C:N ratio. This was attributed to the fact that the added N was broken down and stabilized as pyrrolics and pyridines and protected in the fine fraction. At Sadore, pyrrolics did not persist under conditions of high N availability to microbes most likely because the sandy soil limited SOM protection.

Amides are components of protein that generally decrease in abundance over time because they are a readily accessible and important source of N for microbes (Mengel et al., 1996, Vairavamurthy and Wang, 2002; Gillespie et al., 2014b; Albrecht et al., 2015). Amides may be lower where total N content is higher because N is stimulating decomposition, which was seen in other research (Appel and Mengel, 1990). In the temperate long-term trial mentioned above, amides were most abundant in treatments with higher N input because of greater synthesis and deposition of protein on mineral surfaces with more supplementary N (Gillespie et al., 2014a). In contrast, there are few mineral surfaces at Sadore for microbially synthesized amides to be deposited upon, which is likely why amides are low with highest N. Amides may be higher in the R2F1M2 and R2F0M2 treatments than the R0F0M0 and R2F2M2 treatments because lower fertilizer input relative to organic input stimulated less amide breakdown.

Alkyl-N was lowest in the treatment with high OM and no fertilizer, where amide-N was most abundant, and was similar at all other treatments. N-alkyls are a labile substrate for microbes, derived from proteins (Sjorgersten et al., 2003). Alkyl-N is derived from protein, of which amides is a component, thus alkyl-N is likely low when amides are highest because they have not yet formed from amides. Another important observation is that the alkyl-N peaks for

R2F0M2 and R2F1M2, the treatments highest in organic matter as well as amides, are shifted to the left. This shift indicates that more N is in the nitrate form relative to ammonium (NH_4^+) (Leinweber et al., 2007). Addition of higher intensities of crop residue and/or manure may be stimulating nitrification of NH_4^+ to nitrate (NO_3^-). This was seen in another long-term research trial where increased manure application led to increased NO_3^- production and higher nitrification rates (Müller et al., 2011). Manure may impact nitrification more than crop residue, as residues did not impact nitrification rates after 2 years of addition in another field trial (Hu et al., 2014). These results indicate that the shift in alkyl-N with higher organic matter input may be due to increased nitrification from manure addition. Overall, the amide, pyrrolic, and alkyl-N groups were strongly influenced by the fertility treatments.

Aromatic-, carboxyl-, and carbohydrate- C are all impacted by fertility treatments at Sadore; there was no difference among treatments in abundance of ketone- and phenol- C. Aromatics are more recalcitrant compounds derived through decomposition and humification of lignin in plant material, and they are higher with greater overall nutrient addition (Asselman and Garnier, 2000; Gillespie et al., 2014a; Albrecht et al., 2015). Aromatics increase in relative abundance as humification proceeds and more labile compounds break down or undergo transformation (Leinweber et al., 1993; Vinceslas-Akpa and Loquet, 1997; Sjorgersten et al., 2003; Albrecht et al., 2015). At Sadore, higher abundance of both organic and mineral fertilizer input appears to be a dominant controller of aromatic abundance. This may be because higher fertilizer and OM rates lead to greater crop production and input of lignin-containing millet residues. As well, fertilizer amendment stimulates the breakdown of more labile OM groups, which should increase the relative abundance of aromatics. These results correlate with other research that found higher crop production and nutrient input to the soil increased aromatics (Gillespie et al., 2011). As well, at Sadore where both fertilizer and organic matter input were low at Sadore, aromatics were low, reflecting lack of both stimulant and substrate for OM cycling.

Carboxyls were highest when fertilizer application was low, regardless of the OM rate. Carboxyls increase with degree of humification and are found in plant material as carboxylic acids, as a component of proteins, and as a product of lignin transformation, as well as in microbial matter (Kögel-Knabner, 2002; Mahieu et al., 2000). Carboxyl groups are more resistant against further degradation and their presence represents a higher degree of oxidation (Kiem et al., 2000). With low fertilizer application, one would expect slower decomposition of lignin and thus lower production of carboxyl groups. However, low nutrient availability may also reduce microbial decomposition of carboxyl-containing organic groups that have already formed through humification in more oxidized soils.

Carbohydrates were highest in samples where organic matter inputs were lowest. Carbohydrates are a more readily available and preferentially degraded carbon form, and are released from decomposing polysaccharides. Carbohydrate content tends to decrease as humification proceeds (Sollins et al., 1996; Kögel-Knabner, 2000; Gillespie et al., 2011). Carbohydrates may be higher in the soil with lower OM inputs because the soil is more degraded and soil carbon is stabilized (Gillespie et al., 2011). As well, other research found the breakdown of plant compounds led to breakdown of aromatic groups to carbohydrates (Gillespie et al., 2014a). An inverse relationship between aromatics and carbohydrates is also observed in these Sahelian samples. In contrast, one study of temperate soils found that carbohydrates were lower in depleted soil where fertilizer was not applied, because of lower plant inputs and greater turnover of those inputs (Kiem et al., 2000). Further work is required to elucidate the interactions between nutrient amendment and decomposition/humification processes as they affect carbohydrate transformations in the soil organic fraction.

There may be no difference between any treatments in phenols, recalcitrant plant derived compounds found in lignin (Grandy and Neff, 2008; Wickings et al., 2012), due to a combination of factors. 1) There is a strong similarity of plant biomass in all cases (millet), which may lead to the same abundance of phenols, and 2) phenols are not retained at Sadore because of low content of clay, which adsorbs phenols (Clemente et al., 2011), and dominance of kaolinite in clay mineralogy, which does not typically retain phenol groups (Asselman and Garnier, 2000). There was also no difference among treatments in ketones, which are present in microbial material (Chan et al., 2009; Hitchcock et al., 2009), and produced through microbial metabolism of aromatic (Gottschalk, 1986) and fatty acid (Dent et al., 2004) compounds. Ketones are mainly retained in the fine mineral fraction (Gillespie et al., 2014a), which again is very small at Sadore. Overall, low soil carbon at Sadore may in part be explained by the lack of the fine soil fraction to retain organic groups.

3.7 Conclusions

This study demonstrates that there are both benefits and drawbacks to long-term application of reduced fertilizer rates in the Sahel. The microdosed fertilizer rate provides yield and soil nutrient benefits compared to not adding fertilizer. Soil acidification was also slightly less in soils receiving the reduced rate of inorganic fertilizer versus the recommended rate, which may or may not impact soil functioning. Depletion of plant nutrients not applied in fertilizer, especially K, may be higher with the recommended rate than in the reduced rate soils because of higher yield. More research on mining of nutrients other than K at Sadore would increase understanding on how microdosing impacts soil fertility over time. A potential advantage of the reduced fertilizer rate compared to the recommended rate was in the C and N groups present under each treatment. Treatments with no fertilizer or at the reduced rate along with higher organic inputs were enriched in C and N groups, including amide- and pyrrolic-N, and aromatic-C, that indicated lower SOM breakdown or more substrate for SOM cycling, whereas groups indicating more advanced SOM breakdown, carboxyl-C and alkyl-N, were enriched where fertilizer was higher.

Drawbacks to the reduced rate of fertilizer compared to the recommended rate include lower yields and less increase in soil carbon. Based on the decline in yield trend over sixteen years for the reduced and recommended fertilizer rates, neither fertilizer rate can be considered sustainable; the observed yield decline is likely related to soil acidification, nutrient mining, and overall low SOC. Crop residue and manure addition have the potential to improve sustainability of the reduced fertilizer rate, as crop residue buffered pH at the reduced fertilizer rate, both amendments improved total P, and manure supplied essential plant nutrients that inorganic fertilizer did not, shown by lower N and P levels with higher manure rates. Also, as mentioned above, treatments with higher organic inputs enriched soil with C and N groups suggesting less SOM breakdown. The arid Sahel climate and sandy soil, however, further increase SOM mineralization, inhibiting soil functioning. C and N groups that are normally retained in the fine mineral fraction, including aromatic-, phenol- and ketone-C, and pyrrolic-N, were not protected at Sadore when higher fertilizer inputs favored decomposition. Rates of crop residue and manure higher than 2700 kg ha^{-1}, however, may provide more soil fertility benefits, including improved CEC and OC, increased pH buffering, and improved SOM cycling. The main finding of this study is that reduced fertilizer rate typical of microdosing is no more detrimental to soil functioning than the recommended fertilizer rate; however, application of crop residue and manure at as high of rates as attainable for smallholders is essential for long-term soil fertility and SOM cycling.

4. IMPACT OF INTEGRATED SOIL FERTILITY MANAGEMENT ON SOIL PROPERTIES AND CARBON AND NITROGEN SPECIATION AT LONG-TERM RESEARCH SITES IN THE SAHEL

4.1 Preface[2]

Short-term research has shown that the Integrated Soil Fertility Management (ISFM) approach, which includes the use of mineral fertilizers along with crop residues, manure, and mixed cropping, is effective in improving soil fertility and functioning within the limitations faced by smallholder farmers. More research on the long-term effects of different ISFM techniques on soil fertility is needed. Two long-term research sites, a 16-year trial in Sadore, Niger, and a 50-year trial in Saria, Burkina Faso, incorporate several ISFM techniques. This chapter covers an evaluation of the impact of different rates of fertilizer, crop residue, and manure in both continuous cereal and legume-cereal cropping systems, along with the impact of cultivation and cropping on soil chemical properties and carbon and nitrogen speciation at each site. Results from this research project help to determine practices that will be effective in maintaining soil fertility on smallholder farms.

4.2 Abstract

Low soil fertility severely limits smallholder crop production in the West African Sahel. Both mineral fertilizers and organic amendments such as crop residue and manure benefit soil fertility, but smallholders have difficulty accessing and affording these inputs. Integrated Soil Fertility Management (ISFM) is the joint application of mineral and organic fertilizer inputs along with incorporation of legumes into cropping systems. Short-term research has shown that ISFM benefits soil nutrient content and dynamics; however, little long-term research has been reported on thus far. The research described in this chapter is intended to determine the long-term effect of different ISFM treatments at two long-term research sites in the Sahel of West

[2] Manuscript will be submitted to an academic journal (TBD) for publishing during thesis review process. Coauthors include D. Peak (provided financial assistance, laboratory facilities, ideas, feedback and manuscript editing), J.J. Schoenau (provided ideas, feedback and manuscript editing), A. Gillespie (help with SGM XANES analyses, data processing, and interpretation), G. Kar (significant lab assistance with soil property measurements), S. Koala (PI on INUWAM research project that this research contributes to, provided information on Sadore research site), B. Ouattara (PI on INUWAM project, provided information and involved in Saria research site), A. Kimaro (PI on INUWAM project), A. Bationo (initiated Sadore research site).

Africa, to develop recommendations for sustainable soil fertility management. ISFM treatments at the long-term sites, which have been under cultivation for 16 and 50 years, included several different rates of mineral fertilizer, crop residue, and manure, in both continuous cereal and mixed legume-cereal cropping systems. The long-term impact of cultivation and cropping was also examined by comparison to uncultivated, uncropped soil. Soil chemical properties including pH, soil organic carbon (SOC), cation exchange capacity (CEC), electrical conductivity (EC), total nitrogen (N) and phosphorus (P), and available P were determined. Soil organic carbon (C) and N speciation was determined using the X-ray Absorption Near Edge Structure (XANES) spectroscopic technique. Fertilizer amendment was found to be necessary to maintain soil nutrient content, and manure and crop residue application provided further soil fertility benefits. Crop residue and manure buffered pH decline from fertilizer application, contributed to P fertility, and supplied additional nutrients for plants other than those supplied in the mineral fertilizer source. Only manure was effective for improving SOC and only at the highest rate of 40,000 kg ha^{-1}. Long-term tillage increased N mineralization. Incorporating legumes lowered pH and soil P levels, and only improved soil N at one site. More insoluble P was accessed in the mixed than the continuous cropping system, improving P use efficiency. Mixed cropping with legumes as well as greater organic input led to increased abundance of C and N groups indicative of lower SOM humification. C and N speciation under continuous cereal cropping indicated high levels of SOM decomposition, which is more detrimental to soil functioning. The application of mineral fertilizer and organic matter, especially manure, under mixed cereal-legume cropping is recommended as the best practice to maintain soil fertility and crop production in the Sahel.

4.3 Introduction

Sub Saharan Africa experiences crop production that is less than half of the world average, largely due to low fertilizer use and soil nutrient depletion (Africa Progress Panel, 2014; FAO, 2014). The soil fertility and crop production issues in greater Sub Saharan Africa are exacerbated in the Sahel region by the arid climate and unreliable rainfall patterns (Saïdou et al., 2004). Soil fertility was previously managed through shifting cultivation and expanding cropping area; however, this system has broken down with increased population pressure (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008). Since there is little land to expand cropping, soil fertility must be managed through sustainable intensification of crop input use. Inorganic fertilizer is an important component to meet soil nutrient requirements, but smallholder Sahelian farmers are not able to access or afford sufficient quantities of fertilizer because of poorly developed infrastructure, limited access to financing, and a weak private sector (World Bank, 2014; Vanlauwe et al., 2010). As well, nitrification of N fertilizers increases soil acidity and aluminum toxicity and may lead to yield decline (Pichot et al., 1981; Hue et al., 1991). Application of nitrogen (N) fertilizers may also stimulate mineralization of soil carbon (C), an essential component of soil functioning, further inhibiting yields (Neff et al., 2002; Grandy et al., 2008). Applying organic fertilizers such as crop residue or manure will potentially buffer soil pH decline and improve soil carbon (Bado et al., 2012; Kibunja et al., 2012). Rates of organic amendments like manure that are required to meet crop nutrient requirements are higher than what Sahel farmers generally have access to (Bationo and Mokwunye, 1991; Bayu et al., 2004), thus pairing organic and inorganic inputs is the most feasible way for smallholders to meet crop requirements (Vanlauwe et al., 2010). Using a combination of soil fertility management practices, known as Integrated Soil Fertility Management (ISFM), is a more practical way for farmers to meet crop nutrient demand and build soil fertility.

The goal of ISFM is to maximize nutrient use efficiency and boost crop productivity, and practices in this management approach include joint amendment of inorganic and organic fertilizers, and incorporation of N-fixing legumes into cropping systems (Vanlauwe et al., 2010). ISFM may be the best strategy to improve soil fertility and crop production to improve livelihoods for the many facing food scarcity in the Sahel. There is great potential for ISFM to boost soil fertility and crop production in the Sahel; however more research on the long-term effects of ISFM on soil fertility and nutrient dynamics is needed to develop recommendations for best practices. Short-term research on the effect of ISFM practices on soil in the Sahel has been essential for developing the technique (Geiger et al., 1992; Bagayoko et al., 2000 a,b; Bationo and Ntare, 2000; Yamoah et al., 2002; Mando et al., 2005; Akponikpe et al., 2008, Chivenge et al., 2010; Bationo et al., 2011; Gentile et al., 2013). Long-term agronomic trials are necessary to understand the effect of management practices on long-term soil fertility over several years (Reynolds et al., 2014). The two long-term ISFM research sites that are utilized in the current research have yet to be assessed for their long-term effects on soil fertility. These trials, one of which was established 16 years ago in Niger, and the other over 50 years ago in Burkina Faso, are particularly valuable in revealing long-term effects of IFSM on soil.

The objective of this research is to determine the long-term effect of application of integrated soil fertility management techniques including manure and crop residue application, and mixed cropping with legumes on soil fertility and C and N cycling at two long-term research sites in Sahelian West Africa. We hypothesize that ISFM techniques will result in positive changes to soil fertility and nutrient cycling compared to fertilizer alone, and this hypothesis will be tested through analysis of soil chemical properties and C and N X-ray Absorption Near Edge Structure (XANES) spectroscopy. The XANES technique is used to reveal the type of organic C and N containing compounds in the soil, as affected by the different ISFM treatments. The purpose of this research is to provide scientifically supported recommendations to smallholder farmers in the Sahel that will meet their crop nutrient requirements and maintain the soil resource most effectively with reduced risk.

4.4 Materials and Methods

4.4.1 Site description

Two long-term research trials were used to study the long-term effects of ISFM treatments in the Sahel. The first long-term research trial, known as Sadore, is run by the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Sadore, Niger, established 1993 (Figure 4.1). The second long-term trial, referred to as Saria, is located at the Environment and Agricultural Research Institute (INERA) centre in Saria, Burkina Faso, established in 1965 (Figure 4.1). Annual precipitation at Sadore is 440-587 mm yr^{-1} and mean annual temperature (MAT) is 28.3-28.9 ºC. Saria has a higher annual precipitation, at 735-876 mm yr^{-1} and similar MAT of 27.5-28.2 ºC. The soil type at Sadore is a Hypoluvic Arenosol, according the World Resource Base for Soil Resources classification, described in the previous chapter (Jones et al., 2013). Soil particle size distribution at Sadore is 92% sand. The soil at Saria is a Plinthic Lixisol, slightly acidic with a clay enriched B horizon layer dominated by kaolinite (Jones et al., 2013). Soil particle size distribution is lower in sand than Sadore, at 53%, with 36% silt and 11% clay (B. Outtara, personal communication, 2015).

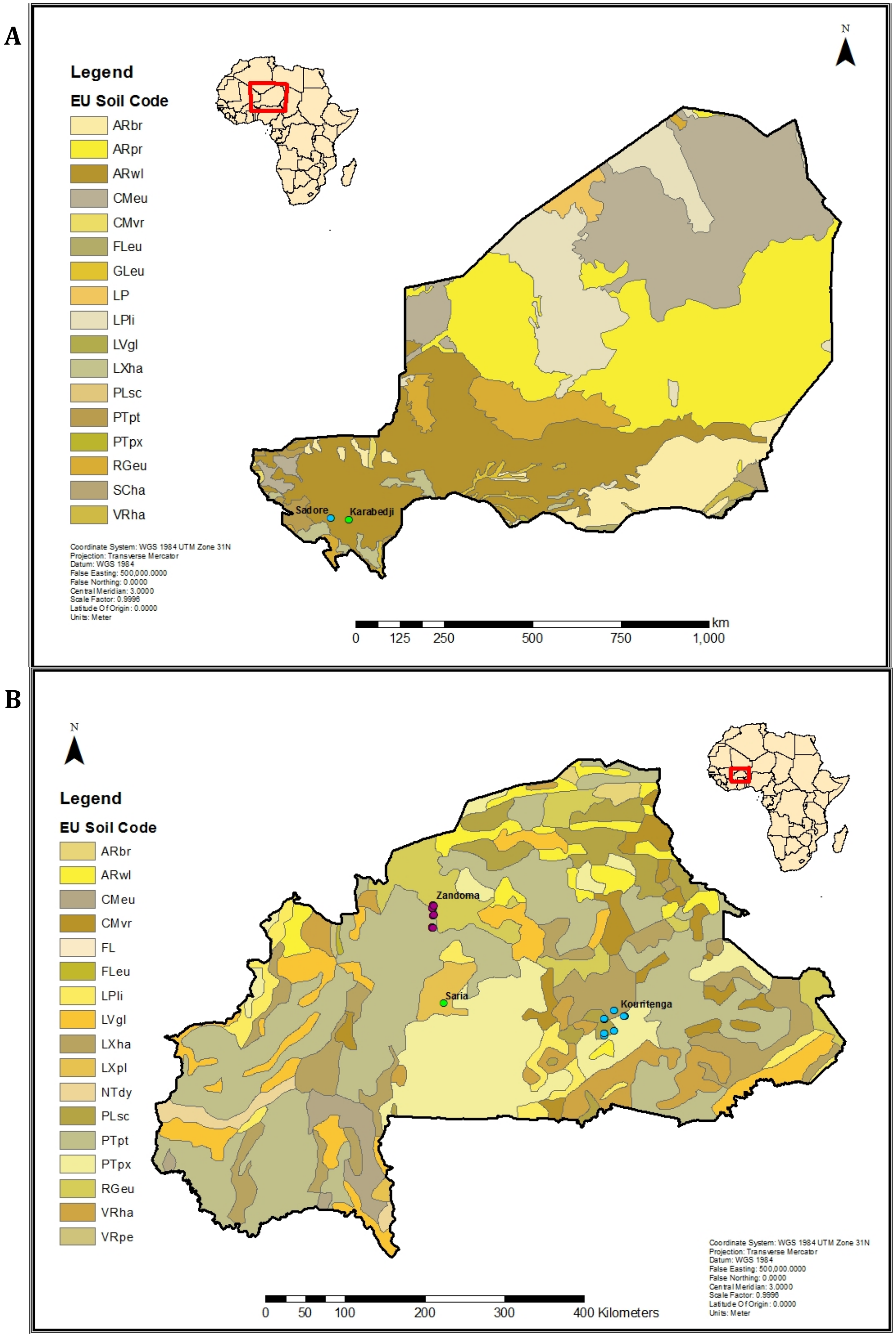


Fig. 4.1. Soil maps of A) Niger with location of Sadore long-term research site, and B) Burkina Faso with location of Saria long-term research site. Sadore site soil type is ARwl, Hypoluvic Arenosol and Saria site soil type is LXpl, Plinthic Lixisol (Adapted from Jones et al., 2013).

The experimental design of the trial at Sadore is RCBD with a 3x3x3x2 factorial layout, the factors being three rates each of mineral fertilizer, crop residue, and farmyard manure and two cropping systems: continuous *Pennisetum glaucum* (millet) and intercrop of millet and *Vigna unguiculata* (cowpea). There were three replications per treatment. The application rates for mineral fertilizer included a control of 0 kg N ha^{-1} and 0 kg P ha^{-1}, a reduced rate of 15 kg N ha^{-1} and 4.4 kg P ha^{-1}, and a regionally recommended rate of 30 kg N ha^{-1} and 13.2 kg P ha^{-1}. In both the reduced and recommended treatments, N was applied as calcium ammonium nitrate (CAN), 10 days after sowing (DAS), placed 10 cm from the site of sowing and incorporated with a hand hoe. P was applied as single super phosphate (SSP), and was broadcast and ploughed into the soil before sowing for both rates of P (Akponikpe et al., 2008). The rates of crop residue and cattle manure amendment were 300 kg ha^{-1}, 900 kg ha^{-1}, and 2700 kg ha^{-1} dry weight for each type of organic matter. Nutrient additions in manure and crop residue treatments are shown in Table 4.1, derived from Akponikpe et al. (2008). Crop residue and manure were applied before sowing; crop residue was broadcast on soil surface as mulch, and manure was broadcast and incorporated into soil. Sowing took place after the first rain, usually in June, but in some years was as early as May or as late as July. In the continuous system, millet was planted with a spacing of 1m by 1m (10000 hills ha^{-1}) and thinned to 30000 plants ha^{-1} after two to three weeks. In the millet-cowpea intercrop, row spacing was 1:1, with millet planted first, at 1.5m by 1m and thinned to 20000 plants ha^{-1}, followed three weeks later, or longer with low soil moisture, by uninoculated cowpea at 1.5 by 0.25m and thinned to 26650 plants ha^{-1}. Hand weeding took place two to three times per season and insecticide was sprayed three to five times in the millet-cowpea intercrop to protect cowpea, which is susceptible to many insects.

The Saria long-term trial was an RCBD design and split plot arrangement, with six different fertility treatments as the main plot, and cropping system as the sub-plot. There were six replications for each treatment and cropping system combination. Cropping systems included continuous *Sorghum bicolor* (sorghum) and a yearly rotation between sorghum and cowpea (uninoculated). The fertility treatments were as follows: 1) unfertilized control, 2) fertilizer alone with 14 kg N ha^{-1}, 23 kg P ha^{-1}, and 14 kg K ha^{-1} as NPK broadcast two weeks after sowing, followed by 23 kg N ha^{-1} broadcast as urea applied 30 days after sowing in the continuous sorghum system only, 3) fertilizer with biennial sorghum straw application (Fert+Residue), with the rate of straw being the amount produced the previous year, which based on average straw yields during the experiment, is approximately 4800 kg ha^{-1}, 4) fertilizer with a low farmyard manure treatment at 5000 kg ha^{-1} dry weight (Fert+LM) applied every 2 years, 5) fertilizer with additional N and K (Fert+NK); fertilizer application from treatment 2, with an additional 23 kg N ha^{-1} as urea for the continuous system only, and an application of K at 30 kg K ha^{-1} for both cropping systems, both broadcast 60 days after sowing, and 6) Fert+NK treatment with 40000 kg ha^{-1} dry weight of farmyard manure (Fert+NK+HM) applied every 2 years. Nutrient addition with sorghum straw and manure by rate is provided in Table 4.1. As well, manure at Saria contained 1.4% Ca, 0.6% Mg, and 0.2% Na, with a C/N ratio of 14.2 and the C/N ratio of sorghum straw at Saria is 304. Organic amendments at Saria were applied before land preparation and incorporated into the soil by tillage. Ploughing of soil and sowing at 31250 planting hills ha^{-1}, with a spacing of 40cm by 80cm for each crop, took place after the first rain, which was generally in the last week of June or early July. Millet and cowpea seeds were treated with insecticide before sowing, and cowpea seed was not inoculated with *Rhizobium spp*.

Table 4.1. Addition of N, P, and K by organic amendment type and rate at Sadore and Saria research sites.

		Rate	N	P	K
Amendment Type	Frequency	kg ha^{-1}			
Saria					
Low manure	Biannual	5000	90.0	10.5	150.0
High manure	Biannual	40000	720.0	84.0	1200.0
Sorghum residue	Biannual	4800	9.6	6.2	32.2
Sadore					
Manure	Annual	300	3.0	0.6	4.8
	Annual	900	9.0	1.8	14.4
	Annual	2700	27.0	5.4	43.2
Millet residue	Annual	300	2.2	0.2	7.6
	Annual	900	6.7	0.5	22.9
	Annual	2700	20.0	1.4	68.6

4.4.2 Soil sampling and chemical analyses

As mentioned in the previous chapter, soil samples from both Sadore and Saria were sent to the University of Saskatchewan prior to the beginning of my Master's research. I did not personally visit the research sites, collect samples, and make my own observations, which would have undoubtedly enhanced interpretation of the data. At Sadore, soil was sampled before sowing in June 2013, and at Saria, soil was sampled nearing the end of the rainy season in September 2013, when crops were at maturity but not yet harvested. Site to site variability may be due to different sampling times; however, the 16 to 50 years of treatments at each site likely account for more of the differences. As well, in the results and discussion, differences within and not between sites are dominantly discussed. At both sites three composited samples were taken at the 0-20 cm depth using an auger. A sub-sample was air-dried, ground to pass through a 2 mm sieve, packaged in individual airtight sealed bags, and shipped to researchers at the University of Saskatchewan in August 2013. When received, each soil sample was transferred to an airtight vial and analyzed from September 2013 to July 2014. Soil was also sampled from adjacent uncultivated land at each site to compare to cropped cultivated land. This soil is covered with dominantly perennial gramineous species, which included *Andropogon gayanus* and *Andropogon ascinodis* at Saria. At Sadore, the adjacent uncultivated soil is mainly dominated by the shrub *Guera senegalensis*.

Soil samples were analyzed for pH, electrical conductivity (EC), organic carbon (OC), total phosphorus (P) and nitrogen (N), available P, and cation exchange capacity (CEC). Three measurements for each soil sample were measured for EC and pH using a glass electrode in a 2:1, water: soil suspension, with 10mL of water and 5 g of soil (Carter and Gregorich, 2008). The LECO-C632 carbon determinator (LECO© Corporation, 1987) was used to analyze two 0.3 g replicates of each soil sample for OC concentration. Low carbon standard reference materials were used for calibration, and a quality control sample of known OC content was measured every twenty analyses. Total N and P were measured according to the acid block digestion method of Thomas et al. (1967). Triplicate samples of 0.25 g ground soil was digested on a heating digestion block at 360°C in 5 mL of concentrated sulphuric acid once for 30 minutes, and then digested eight consecutive times with addition of 0.5 mL of hydrogen peroxide, allowing to cool for 30 minutes between each digestion. Digests are then allowed to cool to room temperature, brought to 75 mL with de-ionized water, mixed, subsampled and analyzed on an auto-analyzer. A standard soil of known total P concentration was used for quality control. Extractable, available P and effective CEC were determined using a Mehlich-3 extraction, as described by Carter and Gregorich (2008). The Mehlich-3 extraction was chosen because of its ability to extract multiple elements of interest to this study, and its applicability to tropical acidic soils (Carter and Gregorich, 2008). Briefly, 100 mL of an ammonium fluoride and ethylene diamine tetra-acetic acid (EDTA) stock solution was added to a solution of ammonium nitrate, acetic acid, 10% nitric acid and deionized water. 30 mL of the extracting solution was added to 3.0 g of soil, shaken for 5 minutes and passed through a Whatman #42 filter paper. Available P was then determined from the Mehlich-3 extracted soil solution using a Technicon™ auto-analyzer. CEC was determined by measuring the concentrations of Ca, Mg, Na, and K in vacuum filtered Mehlich-3 solutions on the Microwave Plasma Atomic Absorption Spectrometer (MP-AES 4100, Agilent Technologies) and concentrations were used to calculate CEC as the sum of exchangeable Ca, Mg, Na, and K. As mentioned previously exchangeable acidity, Al^{3+} and H^{+} concentration, was not determined because of limited soil from each sample

4.4.3 X-ray absorption spectroscopy

Carbon and nitrogen speciation was determined by measuring X-ray Absorption Near Edge Structure (XANES) at the C and N *K*-edges at the Spherical Grating Monochromator (SGM) beamline 11ID-1 at the Canadian Light Source in Saskatoon, Saskatchewan, Canada. At the C and N *K*-edges, the beam line delivers 10^{11} photons s^{-1} with a resolving power of $(E/\Delta E)$ >10,000 (Regier et al., 2007a, b). The energy range for the C *K* -edge is from 270 to 320 eV, and the N XANES *K*-edge is between 380 and 430 eV. Samples were prepared by slurrying a small amount of the soil sample with water, pipetting onto Au-coated Si wafers attached to the sample holder using double-sided carbon tape, and allowing to air dry. The rep for each treatment highest in OC% was selected for XANES measurement to reduce instrument noise because all soil samples were low in C. Soil OC and total N contents, and C:N ratio of samples selected for XANES analysis are all in Table A.1 of Appendix A. After sample preparation, samples were loaded into the SGM end station and brought under vacuum. Data was collected for the C and N *K*-edges separately using the slew scanning mode, in which the monochromator scans the energy range of each element, acquiring data while minimizing X-ray exposure to sample (Gillespie et al., 2015). An average of 60 scans were taken per sample at a new spot on the sample for each scan to avoid radiation damage. The beam line exit slit was set to 25 μm and partial fluorescence yield was collected using one Amptek silicon drift detector. XANES spectral features for C and N types were identified from diagnostic peaks, which have been previously identified from analysis of reference compounds (Leinweber et al., 2010; Myneni, 2002; Urquhart and Ade, 2002). Citric acid was used for calibration at the C *K*-edge where the peak at 288.8 eV was used for energy calibration. Normalization to incident flux (I_0) was carried out by recording the scattering intensity from a freshly sputtered (carbon free) Au surface across the C *K*-edge (Gillespie et al., 2015). The N *K*-edge data was calibrated to the υ=0 vibration of interstitial N_2 gas (at 400.8 eV) in solid-state ammonium sulfate (Gillespie et al., 2008). C and N XANES data was processed using IGOR Pro v.6 software (Wavemetrics, Lake Oswego, Oregon USA). All spectra were normalized to the highest peak. The intercrop and continuous cropping systems C XANES were measured at separate times due to time limitations, and as such, cannot be compared to each other.

4.4.4 Statistical analyses

Mean comparisons of soil properties were performed with PROC MIXED in SAS. The Tukey-Kramer test method of multi-treatment comparison for least significant differences (LSD) was used for mean comparison. At Saria, treatments were analyzed as split plot RCBD, fertility treatments being main plot and cropping system being subplot, with treatments as the main effect and replications as the block (random) effect. At Sadore, effect of manure and crop residue soil properties on soil properties was analyzed as a RCBD, with treatments as fixed effect, and replications as block effect. ANOVA tables for Sadore are found in Appendix A, Tables A.2. to A.8., and Saria ANOVA tables in Appendix B, Tables B.1. to B.7. Fertilizer rates at medium manure and crop residue rates were compared to the uncultivated and uncropped soil as CRD design. Significance for yield regression and soil property mean comparison was declared at $p \leq 0.05$. Data was tested for normality and log transformation was used to ensure normality for EC and available P at both Saria and Sadore, for total P at Saria, and for total N at Sadore. The impact of mineral fertilizer on soil properties at Sadore was discussed in the previous chapter to determine the long-term impact of the different fertilizer rates. In the current chapter, the impact of fertilizer on soil properties at Sadore will only be discussed in comparison to the uncultivated and uncropped soil, so as to not repeat the analysis of the previous chapter. All fertility treatments at Saria will be analyzed.

4.5 Results

4.5.1 Impact of integrated soil fertility management (ISFM) treatments on soil chemical properties at Saria and Sadore

Amongst the fertility treatments at Saria, and compared to the uncultivated soil, pH ranged from 4.2 to 6.4 (Table 4.2). The fert+NK+HM treatment had the highest soil pH but was not significantly different from the control. The fert+residue, fertilizer, and fert+NK treatments had the lowest mean pH. The application of fertilizer decreased pH at Saria, and manure application, especially the high manure rate, buffered the pH decline. Overall, CEC was very low for all treatments, ranging from 0.6 $cmol_c\ kg^{-1}$ to 3.7 $cmol_c\ kg^{-1}$ (Table 4.2). The CEC improved with manure application and was reduced through fertilizer application at this site. The EC was not affected by treatment and salinity is not an issue as all EC levels are well below 4 $mS\ cm^{-1}$. Compared to cultivated and cropped soil, the uncultivated soil was lowest in CEC.

Comparing fertilizer rates to the uncultivated soil at Sadore, pH ranged from 5.0 pH for the uncultivated soil to 5.5 pH for the unfertilized soil (Table 4.3). There was no significant difference in EC with cultivation and cropping. The CEC at Sadore was even lower than Saria, ranging from 0.3 to 0.8 $cmol_c\ kg^{-1}$. The uncultivated soil was significantly higher in CEC than the soil in the fertility rate treatments, which were not different from each other. Soil pH did not change with manure rate (Table 4.3), however, increased crop residue rate led to a small but statistically significantly higher pH, increasing by 0.1 pH units from the low to medium and medium to high rates (Table 4.3). Crop residue or manure rate did not impact soil EC or CEC at this site.

Table 4.2. Soil chemical properties in the continuous sorghum system treatments and uncultivated soil (0-20 cm depth) at Saria.

Treatment	pH	Electrical Conductivity	CEC
		mS cm^{-}	cmol$_c$ kg^{-}
Control[†]	5.8ab[‡]	0.018d	2.1b
Fertilizer	4.3e	0.052bc	1.3cd
Fert+Residue	4.6de	0.033bcd	1.3cde
Fert+LM	5.1cd	0.031cd	1.9bc
Fert+NK	4.2e	0.061ab	1.2de
Fert+NK+HM	6.4a	0.096a	3.7a
Uncultivated/uncropped	5.3bc	0.030cd	0.6e

[†]Treatment abbreviations: Fert=fertilizer; LM=low manure; fert+NK=fertilizer plus additional nitrogen and potassium; HM=high manure.
[‡]Means within a column followed by the same letter are not significantly different (P < 0.05) using Tukey test for LSD.

Table 4.3. Soil chemical properties in fertilizer, manure, and crop residue treatments in the surface (0-20 cm) soil at Sadore site.

Treatment	Rate	pH	EC	CEC
			mS cm^{-}	cmol$_c$ kg^{-}
Fertilized versus	Control[†]	5.5a[§]	0.035a	0.4b
uncropped/uncultivated	Reduced	5.2ab	0.045a	0.3b
soil	Recommended	5.3ab	0.043a	0.5b
	Uncultivated/uncropped	5.0b	0.052a	0.8a
Manure	Low[‡]	5.1b	0.056a	0.6a
	Medium	5.2a	0.052a	0.6a
	High	5.1b	0.046a	0.7a
Crop residue	Low[‡]	5.0c	0.047a	0.5a
	Medium	5.1b	0.053a	0.6a
	High	5.2a	0.054a	0.7a

[†]Control, reduced and recommended rate correspond to 0 kg ha^{-1} N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer.
[‡]Low, medium, and high crop residue and manure rates correspond to 300, 900, and 2700 kg ha^{-1} crop residue added per year for 16 years.
[§] Means followed by the same letter within each treatment in a column are not significantly different at P < 0.05 according to Tukey's LSD test.

At both Saria and Sadore (Table 4.4), the mixed cropping systems incorporating legumes had slightly (about 0.1 pH unit) lower pH than the continuous cereal systems. There was no significant difference in EC between cropping systems at either site. At Saria, the continuous cropping system had significantly higher CEC, but there was no difference in CEC between systems at Sadore.

Table 4.4. Soil chemical properties in surface (0-20 cm) soil of cropping treatments at Saria and Sadore sites.

Research Site	Cropping System	pH	EC	CEC
			mS cm^{-}	cmol$_c$ kg^{-}
Saria	Continuous sorghum	5.1a[†]	0.049a	2.2a
	Sorghum-cowpea rotation	5.0b	0.058a	2.0b
Sadore	Continuous millet	5.2a[†]	0.049a	0.4a
	Millet-cowpea intercrop	5.1b	0.053a	0.8a

[†]Means followed by the same letter within each site in a column are not significantly different at $P < 0.05$ according to Tukey's LSD test.

4.5.2 Impact of ISFM treatments on soil carbon and nutrients

Comparing effects of fertility treatments on soil at Saria (Table 4.5), the fert+NK+HM treatment had higher OC, total and available P, and total N than all the other treatments. No other treatments were significantly different from each other in SOC concentration, including the uncultivated and uncropped soil. There was no difference in total P between any other fertilizer treatments, which were all higher than the control treatment and the uncultivated and uncropped soil. After the fert+NK+HM treatment, the fertilizer alone, fert+NK, and fert+LM treatments were next highest in available P, followed by the fert+residue treatment. The control and uncultivated/uncropped soils were much lower in available P than all fertilized treatments. The uncultivated/uncropped soil was next highest in total N, after fert+NK+HM, and was not significantly different from the other fertilizer treatments, which were not significantly different from the control.

Table 4.5. Soil carbon, total and available P, and total N in surface (0-20 cm) soil in continuous sorghum system treatments and uncultivated soil at Saria.

Treatment	OC	Total P	Available P	Total N
	%	mg kg-	mg kg-	mg kg-
Control	0.30b†	88.0c	5.9d	77.4c
Fertilizer	0.40b	165.1b	62.4b	123.0bc
Fert+Residue	0.29b	126.9b	37.6c	99.5bc
Fert+LM	0.48b	152.7b	54.8bc	148.8bc
Fert+NK	0.35b	139.7b	46.9bc	111.7bc
Fert+NK+HM	0.98a	256.7a	135.2a	426.4a
Uncultivated/uncropped	0.45b	69.4c	0.1d	179.7b

†Treatment abbreviations: Fert=fertilizer; LM=low manure; fert+NK=fertilizer plus additional nitrogen and potassium; HM=high manure.
‡Means within a column followed by the same letter are not significantly different ($P < 0.05$) using Tukey test for LSD.

At Sadore, the soil OC was low for all fertilizer treatments, and increasing manure and crop residue rates led to small increases in OC, increasing from 0.24% to 0.27% OC with both amendments (Table 4.6). The medium manure rate was not significantly different from either the low or high manure rate and the medium crop residue rate was not different from the low rate. Total P increased significantly with both manure and crop residue application. Manure amendment had a greater effect on soil total P content than crop residue. Increased manure rate did not increase available P, as levels were highest at the low manure rate and lowest at the medium manure rate. There was no significant difference in available P or total N among crop residue rates. Manure applied at the lowest rate was highest in total N and there was no difference between the medium and high manure rates. In general, at Sadore, total P content of the soil was improved with manure and crop residue application, however, neither amendment greatly improved soil OC, available P or total N.

At Sadore, cultivation and cropping did not impact soil OC, as there was no significant difference in OC between the uncultivated uncropped soil and the cultivated soils despite fertilizer amendment (Table 4.6). The recommended fertilizer rate and uncultivated soil had similar total N concentration and the control and reduced fertilizer rates were significantly lower in total N. All fertilizer rate treatments had significantly higher total P than the uncropped and uncultivated soil, and were not different from each other. Available P increased with fertilizer rate from the control to the high rate, and there was no difference in available P between the control and uncultivated/uncropped soil.

Table 4.6. Soil OC, total and available P, and total N in the surface (0-20 cm) soil of treatments at Sadore site.

Treatment	Rate	OC	Total P	Available P	Total N
		%	mg kg^{-}	mg kg^{-}	mg kg^{-}
Fertilized versus uncropped/uncultivated soil	Control[†]	0.26a[†]	163.0a	4.0bc	79.4b
	Reduced	0.26a	190.2a	6.8b	89.8b
	Recommended	0.26a	194.4a	24.5a	133.9a
	Uncultivated/uncropped	0.21a	82.3c	3.0c	131.0a
Manure	Low[§]	0.24b	131.8c	14.7a	123.5a
	Medium	0.26ab	163.1b	11.6b	104.2b
	High	0.27a	184.0a	13.3ab	99.9b
Crop residue	Low[§]	0.24b	152.4b	13.4a	107.0a
	Medium	0.25b	159.4ab	14.5a	107.1a
	High	0.27a	167.1a	11.8a	113.5a

[†]Control, reduced and recommended rate correspond to 0 kg ha^{-1} N and 0 kg ha^{-1} P, 15 kg ha^{-1} N and 4.4 kg ha^{-1} P, and 30 kg ha^{-1} N and 13.2 kg ha^{-1} P respectively applied per year for 16 years as CAN and SSP fertilizer.
[‡]Low, medium, and high crop residue and manure rates correspond to 300, 900, and 2700 kg ha^{-1} crop residue added per year for 16 years.
[§] Means followed by the same letter within each treatment in a column are not significantly different at $P < 0.05$ according to Tukey's LSD test.

At both Saria and Sadore there was no significant difference in OC between the cropping systems (Table 4.7). For both research sites, the continuous cereal system was significantly higher in total P than the mixed legume cropping system. At Saria, available P was higher in the continuous system compared to the sorghum-cowpea rotation. There was no difference between systems in available P at Sadore and levels were much lower than at Saria. At Saria, there was no significant difference in total N. At Sadore, however, total N was significantly higher in the intercrop than the continuous millet system.

Table 4.7. Soil carbon, total and available P and total N by cropping system in surface (0-20 cm) soil at Saria and Sadore sites.

Site	Cropping System	OC	Total P	Available P	Total N
		%	mg kg⁻	mg kg⁻	mg kg⁻
Saria	Continuous sorghum	0.49a†	172.3a	46.9a	208.7a
	Sorghum-cowpea rotation	0.46a	134.8b	30.7b	207.1a
Sadore	Continuous millet	0.26a	180.6a	13.4a	102.3b
	Millet-cowpea intercrop	0.25a	138.6b	13.0a	116.1a

†Means followed by the same letter within each site in a column are not significantly different at $P < 0.05$ according to Tukey's LSD test.

4.5.3 Impact of ISFM treatments on C and N forms as identified by XANES

Based on the XANES analysis, the abundance of both C and N functional groups in soil organic matter (SOM) at the Saria site varied between cropping systems, fertility treatments and with cultivation and cropping. Differences in C speciation between cropping systems were largest for the ketone and phenol groups, peaks 2 and 3 respectively (Fig. 4.2). The rotation was higher than the continuous in ketones and phenols for all treatments, except the control and fert+residue treatments. The difference between cropping system in ketones and phenols was especially high in the fertilizer alone treatment where there were no organic inputs. Continuous sorghum was higher in peak 5, carbohydrate-C, than the rotation for the fertilizer, fert+LM, and fert+NK treatments.

Both cultivation and fertility treatments had an impact on C speciation in the continuous cropping system (Fig. 4.2). The uncultivated and fert+NK+HM spectra were highest in aromatics and ketones and lowest in carbohydrates. The uncultivated soil was higher in phenols than all treated soils, of which fert+NK+HM was the highest. The treatments highest in carbohydrates were the control, fertilizer alone, and fert+NK treatments. There was no difference between other treatments in aromatics, ketones, or phenols. The uncultivated soil was also lower than all treatments in carboxyl-C, peak 4.

Differences in N speciation between cropping systems at Saria was largest for amide-N, peak 2; continuous sorghum was depleted in amides compared to the rotation for each fertility treatment (Fig 4.3). The continuous system was higher than the rotation in pyrrolic-N, peak 3, for only the fert+residue treatment, and was higher in N-bonded aromatic-N, peak 4, for both the fert+residue and fert+NK treatments. Peak 5, alkyl-N, was shifted to the left in the continuous system compared to the rotation for all treatments but especially the fert+NK, fertilizer alone, fert+LM, and control treatments. The uncultivated soil was higher in amides than all the fertility treatments and was lower in peak 1, pyridines and pyrazines, than all treatments except fert+NK.

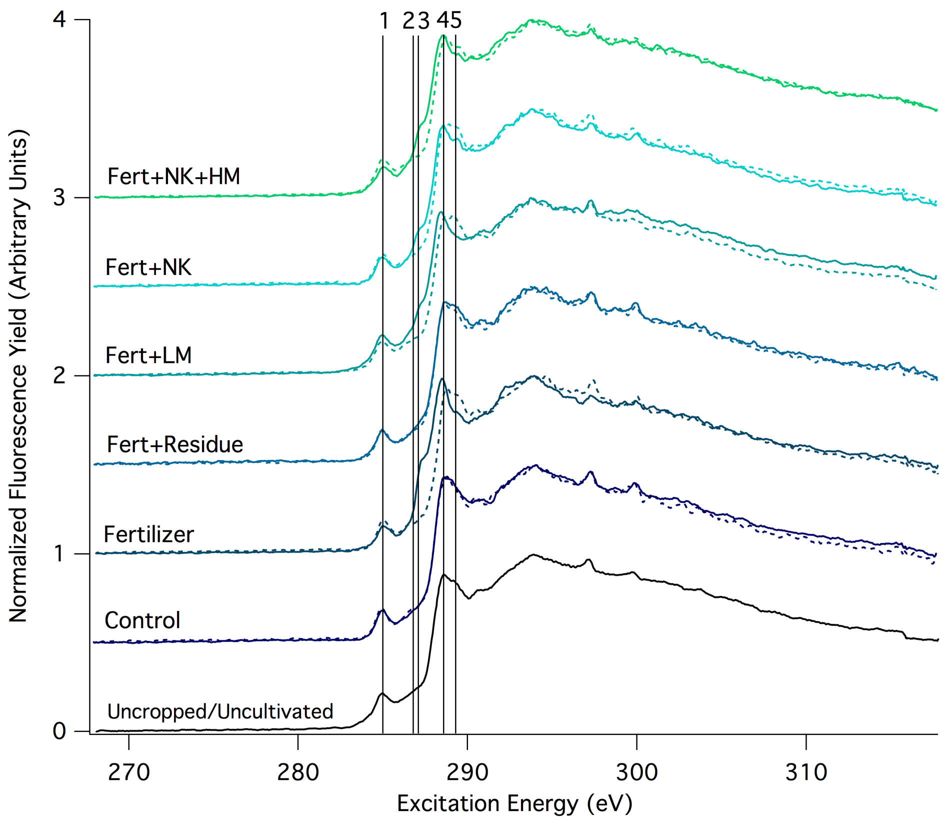


Fig. 4.2. Normalized fluorescence yield of C *K*-edge XANES spectra of surface soils at Saria in ISFM treatments and adjacent uncropped/uncultivated soil. Continuous sorghum is the dotted line and sorghum-cowpea rotation is the solid line. Fert = fertilizer, LM = low manure, HM = high manure, fert+NK = fertilizer with additional N and K. Carbon features corresponding to specific excitation energy are identified as: 1. aromatic C at 285 eV; 2. ketones at 286.8 eV; 3. phenolic at 287.1 eV; 4. carboxylic at 288.6 eV; 5. carbohydrate hydroxyl at 289.6 eV.

The amides were the N group varying most between fertility treatments in the continuous system at Saria (Fig. 4.3). Pyrrolic and N-bonded aromatic groups also varied among the treatments. The fert+NK+HM treatment was highest in amides, pyrrolics, and N-bonded aromatics, followed by the control and fertilizer treatments with lower organic matter rates (fert+residue and fert+LM), followed by the fertilizer alone treatment. The fert+NK treatment was similar in N-bonded aromatics abundance as the fertilizer alone treatment, but was lower in amides and pyrrolics.

Cultivation had a large impact on C XANES at Sadore (Fig. 4.4, 4.5). Compared to the continuous millet system, the uncultivated/uncropped soil was higher in ketones and phenols. The uncultivated soil and R0F0M0 treatment were highest in carboxyls and R2F1M2 and R2F2M2 were lowest. As well, the carboxyl peak was shifted to the left for the uncultivated soil compared to the cropped and cultivated soil. Both the R2F2M2 and uncultivated soils were higher in aromatics than other treatments. R2F1M2 and the uncultivated soil were lower than all

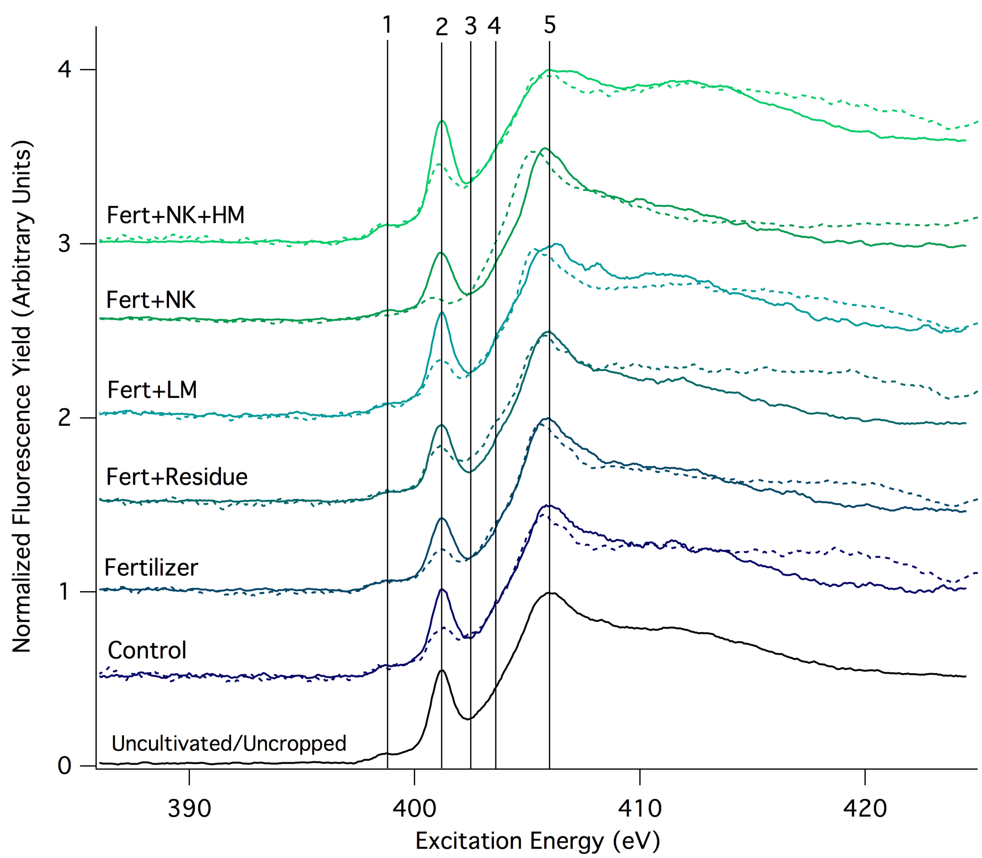


Fig. 4.3. Normalized fluorescence yield of N *K*-Edge XANES spectra of surface soils at Saria in ISFM treatments for each cropping system and adjacent uncropped/uncultivated soil. Continuous sorghum is the dotted line and sorghum-cowpea rotation is the solid line. Treatment abbreviations same as in Fig. 4.2. Nitrogen features corresponding to specific excitation energy are identified as: 1. pyridines and pyrazines, aromatic N in 6-membered rings at 398.8 eV; 2. amides at 401.2 eV; 3. pyrrolic, N in 5-membered rings with unpaired electrons, at 402.5 eV; 4. N-bonded aromatics at 403.5-403.8 eV; 5. alkyl-N at 406 eV.

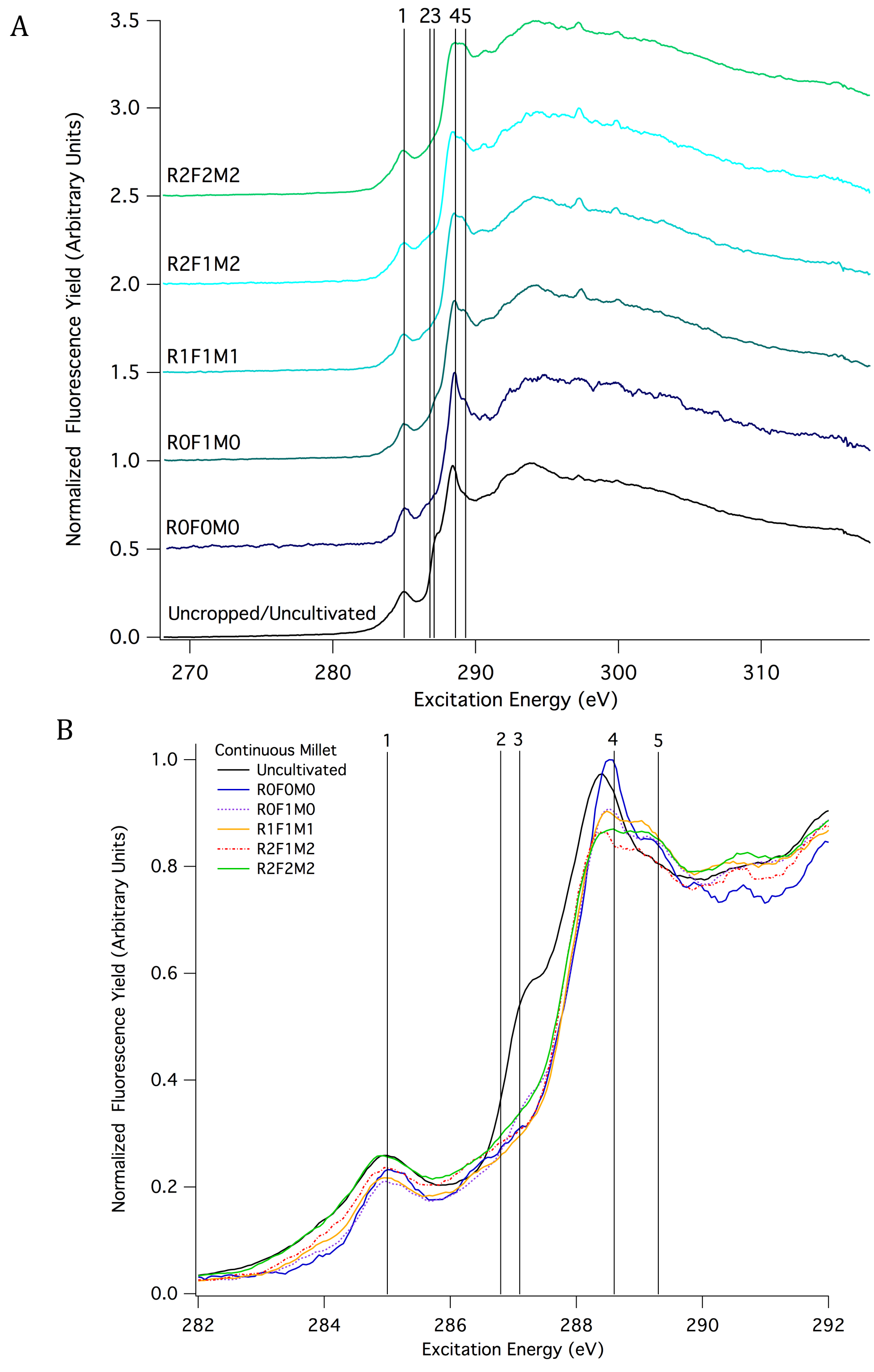


Fig. 4.4. Normalized fluorescence yield of C *K*-edge XANES spectra of surface soils in Sadore site treatments. A) continuous millet cropping system, B) continuous millet cropping system with treatments overlain at 282 eV to 292 eV. R=residue, F=fertilizer, M=manure; F0=control, F1=reduced rate, F2=recommended rate; R0 and M0= low rate, R1 and M1= medium rate, R2 and M2=high rate. Carbon features corresponding to specific excitation energy are identified as: 1. aromatic C at 285 eV; 2. ketones at 286.8 eV; 3. phenolic at 287.1 eV; 4. carboxylic at 288.6 eV; 5. carbohydrate hydroxyl at 289.6 eV.

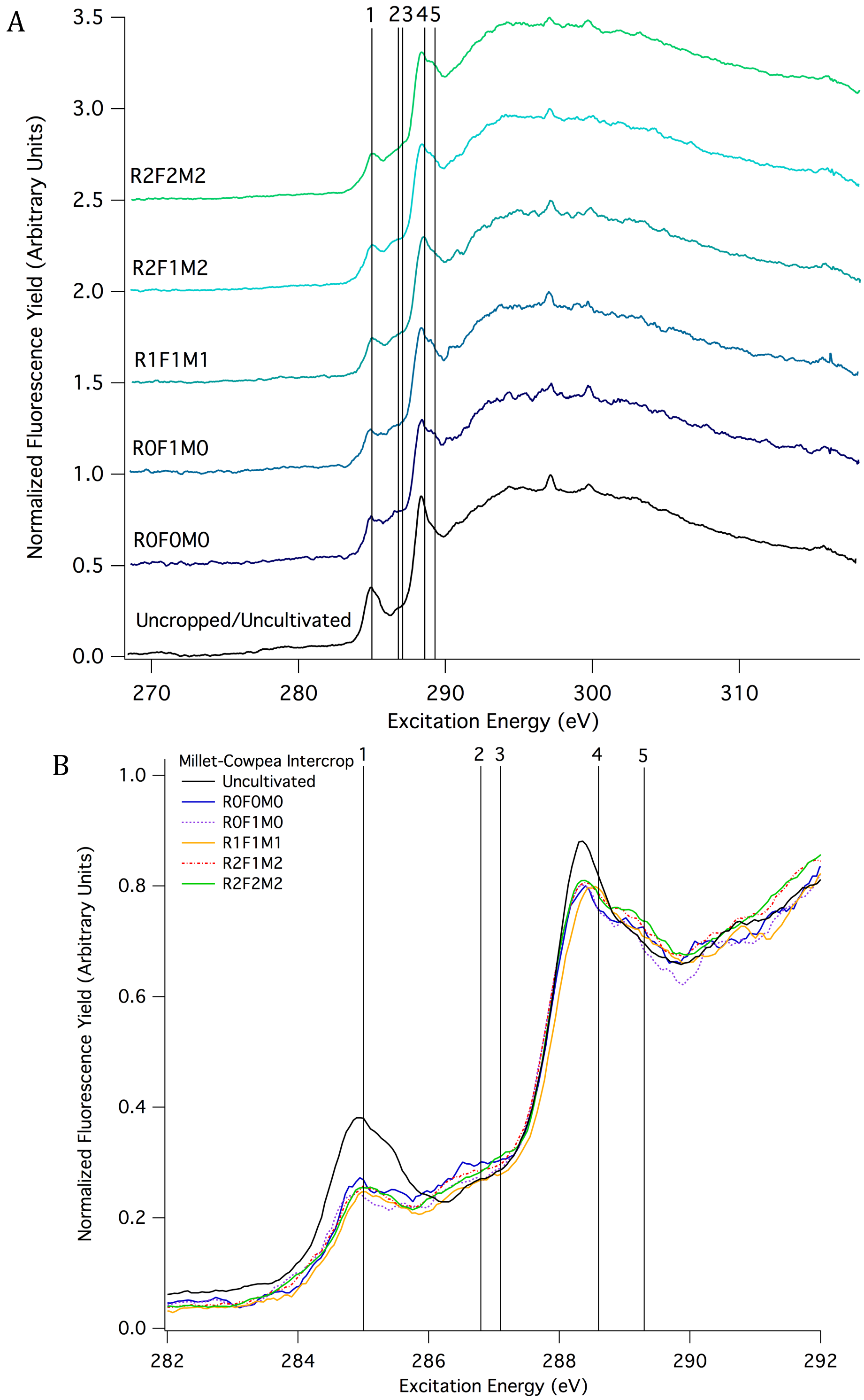


Fig. 4.5. Normalized fluorescence yield of C *K*-edge XANES spectra of surface soils in Sadore site treatments. A) millet-cowpea intercrop system, and B) millet-cowpea intercrop system with treatments overlain at 282 eV to 292 eV. Abbreviations of soil treatments are same as for Fig. 4.4. Carbon features corresponding to specific excitation energy are identified as: 1. aromatic C at 285 eV; 2. ketones at 286.8 eV; 3. phenolic at 287.1 eV; 4. carboxylic at 288.6 eV; 5. carbohydrate hydroxyl at 289.6 eV.

other treatments in carbohydrates. There was little difference in C group abundance between any fertility treatments in the millet-cowpea intercrop. The uncultivated soil was higher in aromatic- and carboxyl-C than the treated soils. There was no difference, however, between the cropped/cultivated and uncropped/uncultivated soil in ketone and phenol abundance, which was notably different from the continuous millet system.

As with the C XANES, cultivation and cropping also impacted N XANES at Sadore (Fig. 4.6). Contrary to Saria, at Sadore the uncultivated soil was lower than the cultivated treated soil in amides, pyrrolics, N-bonded aromatics, and alkyl-N, with no difference in pyridines and pyrazines.

When comparing cropping systems at Sadore, only the highest intensity treatment (R2F2M2) had N speciation differences between cropping systems (Fig. 4.6). For R2F2M2, the millet-cowpea intercrop was higher than continuous millet in amides, which was similar to Saria, but was also higher in pyrrolic groups, and N-bonded aromatics, which was opposite to observations at Saria site.

Amongst the fertility treatments in the continuous millet system at Sadore, amides and N-bonded aromatics were both highest in the R2F1M2 treatment (Fig. 4.6). After R2F1M2, all other treatments were similar in N-bonded aromatics. The R2F2M2 and R1F1M1 treatments were next highest in amides, followed by R0F0M0, then R0F1M0, which was also lower in pyrrolics than all treatments, which were similar in abundance.

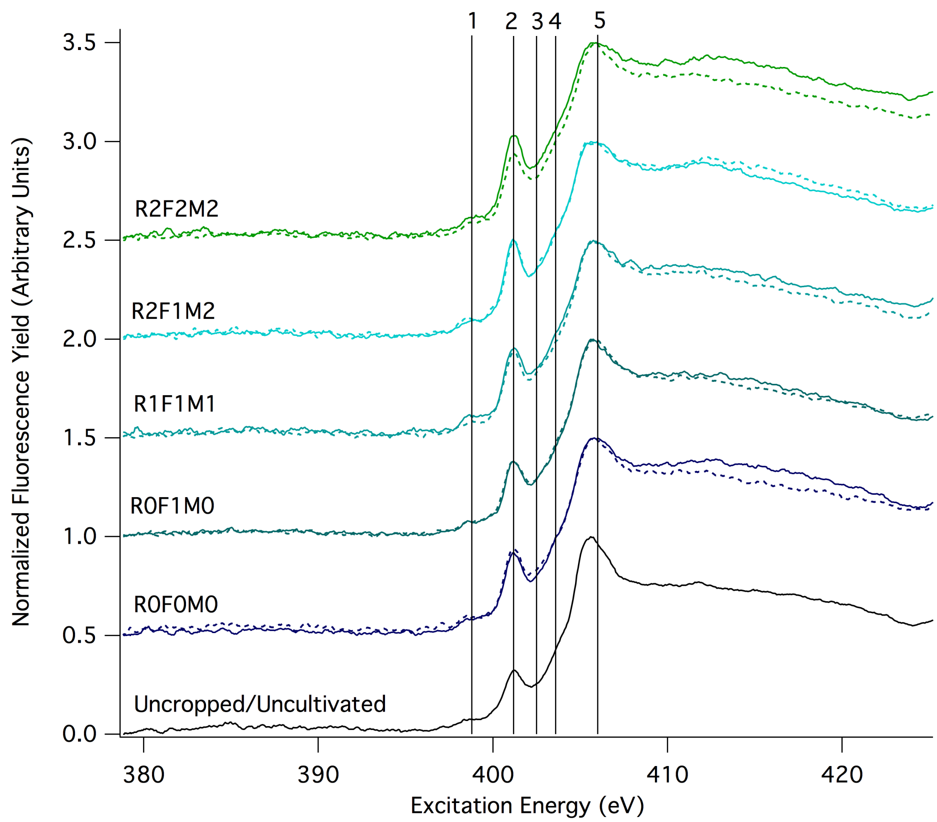


Fig. 4.6. Normalized fluorescence yield of N *K*-edge XANES spectra of surface soils in Sadore site treatments. Continuous millet is the dotted line and millet-cowpea rotation is the solid line. Abbreviations of soil treatments are same as Fig. 4.4. Nitrogen features corresponding to specific excitation energy are identified as: 1. pyridines and pyrazines, aromatic N in 6-membered rings at 398.8 eV; 2. Amides (protein) at 401.2 eV; 3. pyrrolic, N in 5-membered rings with unpaired electrons, at 402.5 eV; 4. N-bonded aromatics at 403.5-403.8 eV; 5. alkyl-N at 406 eV.

4.6 Discussion

4.6.1 Impact of ISFM treatments on soil chemical properties

The ability of manure and crop residue to improve soil pH and CEC at Sadore and Saria is dependent on rate and site. Crop residue application at 4800 kg ha^{-1} at Saria was not enough to significantly increase pH or CEC; however, the medium and high crop residue rates at Sadore (900 and 2700 kg ha^{-1} respectively) did reduce soil acidity. Both pH and CEC were increased in a trial in Niger when 10000 kg ha^{-1} of millet straw was applied (de Ridder and van Keulen, 1990), and 2000 kg ha^{-1} of crop residue improved soil pH compared to fertilized and untreated soil without crop residue application in another long-term Sahel trial (Kretzschmar et al., 1991). In a long-term trial in Niger, soil pH increased above the untreated soil by the same amount with crop residue either at 1600 kg ha^{-1} with no fertilizer applied or at 4000 kg ha^{-1} with N fertilizer applied at 30 kg N ha^{-1}, (Geiger et al., 1992). Therefore crop residue is a means to buffer the acidifying effect of N fertilizer that has been noted in other research projects in the Sahel (Bado et al., 2012; Kibunja et al., 2012). Overall, amendment with crop residue may increase soil pH towards neutrality but likely will not greatly increase the soil CEC in the Sahel.

At Sadore and Saria, only the high manure rate (40000 kg ha^{-1}) with fertilizer at Saria increased both pH and CEC above the untreated soil. Manure at rates up to 2700 kg ha^{-1} did not impact pH or CEC at Sadore. The low manure rate (5000 kg ha^{-1}) with fertilizer in the fert+LM treatment at Saria did increase soil pH compared to fertilizer alone, but was lower in pH than the untreated soil, indicating manure at this rate could not fully buffer the increased acidity arising from N fertilizer application (Bado et al., 2012; Kibunja et al., 2012; Manna et al., 2005). Similar effects on pH and CEC from manure amendment at 5000 kg ha^{-1} have been noted in other long-term tropical research trials (Pichot et al., 1981; de Ridder and Van Keulen, 1990; Goladi and Agbenin, 1997; Manna et al., 2005; Eche et al., 2013). Higher manure rates of up to 40000 kg ha^{-1} appear necessary to increase both soil pH and CEC as noted in other tropical studies (Pichot et al., 1981; de Ridder and Van Keulen, 1990; Cai et al., 2014). CEC did not increase along with pH with any residue or manure rate at either site, except for the high manure rate at Saria. This may be because soil organic matter is more correlated to CEC than pH in the Sahel (Manu et al., 1991). Although increased soil pH and CEC can improve soil nutrient retention and availability, capacity needs to be built to increase smallholder access to crop residue and manure sources for their land.

Cultivation and cropping system did not have as great an effect on pH as manure and crop residue addition did, and effects were different at the two sites. At Sadore, the uncultivated and uncropped soil was lower in pH. The uncropped and uncultivated soil had lower CEC than all treatments at Saria, which may be because crop biomass production contributes to greater recycling of base cations from depth in the cropped soils (Kretzschmar et al., 1991; Noble and Randall, 1999). At Sadore the uncultivated and uncropped soil was slightly higher in CEC, but all soils were very low so it is anticipated that the difference would not affect soil functioning. Soil pH and CEC was higher in no-till treatments than with ploughing in some West African long-term trials (Babalola and Opara-Nadi, 1993; Lal, 1997) that may be related to increases in organic matter content but soil pH did not decline over time with tillage in other trials (Subbarao et al., 2000; Jaieyoba, 2003). Factors influencing pH and CEC at Saria and Sadore appear to be the addition of fertilizer, which lowers the pH, and addition of crop residue and manure that raise soil pH and CEC, as crop residues and manures appear to have value as buffers against the acidifying effects of the fertilizer.

Soil pH was higher in the continuous system than in the mixed legume cropping system at both sites, and CEC was higher in the continuous than the legume containing rotation at Saria, but was not different between systems at Sadore. Soil pH may be lower in the mixed systems because legume residue contributes more N to the soil than cereals, that will undergo nitrification and generate more acidity (Tang and Yu, 1999; Xu et al., 2006; Formowitz et al., 2009). However, the pH difference in this study was not large and in other research in the Sahel region there was no difference in pH between millet-cowpea rotation and continuous millet in long-term trials (Bationo and Ntare, 2000; Bado et al., 2012). In one long-term trial in Mali, the surface soil pH was higher in the cowpea-sorghum rotation than continuous sorghum because of greater biomass input in the mixed system from higher yields, which decomposed and buffered pH (Kouyate et al., 2012). Related to the current research, in some work, pH was lower under cowpea residues than millet or sorghum because there was greater release of organic acids from cowpea root residues at a Sahel trial (Bagayoko et al., 2000a). This may also explain why CEC is lower in the legume containing rotation at Saria in the current research. As at Sadore, there was no difference in CEC between systems in other Sahel trials involving both millet and sorghum with cowpea (Bationo and Ntare, 2000; Bado et al., 2012; Kouyate et al., 2012). There may be a difference in CEC at Saria but not at Sadore because there are similar base cation contents in cowpea and millet residues, but cowpea is significantly lower than sorghum in K, and slightly higher in Mg, both of which contribute to total CEC (Adamu et al., 2014).

4.6.2 Impact of ISFM treatments on soil nutrients

As with pH and CEC, only the high manure rate (40000 kg ha^{-1}) treatment at Saria improved SOC to a large enough extent that it may impact soil functioning. The low manure rate (5000 kg ha^{-1}) and residue treatments at Saria were not significantly different in OC% from treatments with fertilizer alone. As well, increased manure and crop residue rates at Sadore increased OC, but only by 0.03% for each amendment. At long-term trials in more humid regions of Africa with similar soil, manure at 3000 to 10000 kg ha^{-1} improved SOC compared to fertilizer alone (Kapkiyai et al., 1998; Janssen et al., 2011; Bado et al., 2012; Kibunja et al., 2012). The potential gains in SOC are likely to be lower in the Sahel than these other regions because along with high OC decomposition due to year round high temperature, the arid climate leads to lower biomass input (Kapkiyai et al., 1998; Yamoah et al., 2002; Janssen, 2011; Eche et al., 2013). As well, soil at Sadore is very sandy, and SOC accrual is more difficult in sand than clay soil (Zingore et al., 2007; Dunjana et al., 2012; Gentile et al., 2013). In other long-term work at Sadore, manure at 6000 kg ha^{-1} increased SOC, indicating this rate may compensate for climate and soil texture favouring SOC decomposition in the Sahel (Nakamura et al., 2012). In other long-term Sahel research, retention of crop residues either did not improve OC compared to residue removal (Kapkiyai et al., 1998; Buerkert and Lamers, 1999; Yamoah et al., 2002), or improved OC compared to no residue application but reduced OC compared to initial values (Buerkert et al., 2000). Lack of OC improvement may be because crop residue rates are not high enough (Bationo and Buerkert, 2001), because the high C:N slows decomposition of the residue to SOC (Ouédraogo et al., 2007), or because residues decompose quickly in Sahel conditions (Bationo et al., 1995). Based on the literature and current research, manure application at 6000 kg ha^{-1} or higher is the best option to maintain and improve SOM content in the Sahel climate, and although the high manure rate at Saria was effective in improving SOC, 40000 kg ha^{-1} is likely not realistic for farmers to apply.

As with OC, the high manure rate of 40000 kg ha^{-1} at Saria increased total and available P and total N more than all other treatments. The high manure rate at Saria is eight times higher than the low rate, and nearly fifteen times higher than the high manure rate at Sadore, and thus adds much more N and P overall. The low manure treatment at Saria does not increase soil total N and P or available P compared with fertilizer alone even though it adds 90 kg ha^{-1} more N and 10.5 kg ha^{-1} more P every year. Total P may not be increasing with the low manure and residue treatments at Saria because the P added with these amendments is being mineralized and taken up by plants to meet P demand (Reddy et al., 2000). The same demand-induced solubilization of organic P was noted with crop residue application in other Sahel research (Hafner et al., 1993). At Sadore, however, increased organic matter improved soil total P, especially for manure because of the greater P content compared to crop residue, but available P and total N were unaffected by either organic treatment. Total P also increased with 2000 kg ha^{-1} of crop residue, with and without fertilizer at a trial in Niger (Kretzschmar et al., 1991). This improvement in total P at Sadore indicates that across fertilizer rates, not all P from organic inputs is being taken up by plants, and may be contributing to residual P buildup. This is also likely occurring at Saria in the high manure treatment because of the large P addition. Residual P is built up when added P is dissolved and sorbed to soil components surrounding the point of application and often forming less soluble compounds that can later be dissolved and taken up by plants (Wolf et al., 1987). Manure and fertilizer application together had increased P uptake in research in India because manure reduced P sorption and increased the recovery of P added in both manure and fertilizer (Reddy et al., 2000). Total P is being taken up at lower crop residue and manure rates at Saria because of crop P demand, but total P increases with organic matter amendment rate at Sadore likely because P demand is being met with fertilizer application.

Except for the high manure rate at Saria, crop residue and manure did not improve available P at either site, and fertilizer and residue at Saria was lower in available P compared to fertilizer alone. In other Sahelian research, crop residue at 2000 to 5000 kg ha^{-1} did not increase available P concentration compared to control (Yamoah et al., 2002; Knewtson et al., 2008), where other research with residues at 1400 to 4000 kg ha^{-1} did see an increase in available P, although it was lower than with fertilizer application (Kretzschmar et al., 1991; Geiger et al., 1992). Based on the current research and mixed results in the literature, large increases in available P from crop residue application would not generally be anticipated in the Sahel region. However, available P will likely increase with manure application at higher rates, as 10000 kg ha^{-1} but not 5000 kg ha^{-1} increased available P over 15 years in Kenya (Kihanda et al., 2012), and manure at 17000 kg ha^{-1} but not 6000 kg ha^{-1} improved available P over three years in Zimbabwe (Zingore et al., 2007). Fertilizer is a more efficient way to improve P availability than manure, as 5000 kg ha^{-1} of manure, which supplied 20 kg P ha^{-1}, was 33% lower in available P than the addition of 17.5 kg P ha^{-1} as phosphate rock (Bationo and Mokwunye, 1991). Manure and crop residue may not be improving available P as much as fertilizer because OM does not contain as much available P (Knewtson et al., 2008). Some P may remain immobilized in the SOM, and the OM decomposition may not supply enough organic acids to chelate with P sorbing Fe and Al oxides and mineral surfaces to release substantial P to the soil solution (Hue et al., 1991; Manu et al., 1991; Sharpley and Moyer, 2000; Braos et al., 2015). Although there are several soil fertility benefits of crop residue and manure amendment, application of fertilizer along with organic matter is likely needed to meet immediate crop P requirements.

At Saria, all manure, crop residue, and fertilizer treatments were higher in total N than the control treatment, but only the high manure treatment was higher than with fertilizer alone. At Sadore, total N did not increase with organic amendment, and manure may have even negatively impacted total N, as the lowest manure rate is highest in total N. Other researchers have noted an increase in total N with 5000 kg ha^{-1} of manure (Bationo and Mokwunye, 1991; de Rouw and Rajot, 2004), or an increase in total N with manure application but only with conservation tillage practices (Mando et al., 2005). Crop residue at 2000 kg ha^{-1} did not improve total N in other research (Buerkert and Lamers 1999). The lack of a difference in total N between fertilizer alone and with manure and crop residue may be because of increased crop growth, N uptake and removal in harvest with the organic amendment treatments compared to fertilizer alone. Manure and crop residue add micronutrients and base cations above and beyond N and P that may be limiting in the soil (de Ridder and van Keulen, 1990; Geiger et al., 1992; Srivastava et al., 2002). At Saria, the low manure rate adds 100, 70, 30, and 10 kg ha^{-} of K^{+}, Ca^{2+}, Mg^{2+}, and Na^{+} respectively, along with N and P. Addition of these nutrients not provided in fertilizer would further improve yield and increase demand and uptake of N (de Ridder and van Keulen, 1990). N uptake may be further maximized through integrated organic and inorganic fertilizer through synchronization. OM addition increases C:N ratio leading to microbial immobilization of N earlier in the season that is later released to plants through microbial turnover (Sugihara et al., 2002; Kuzyakov and Xu, 2013). This leads to fewer N losses and greater N use efficiency (Vanlauwe et al., 2010; Gentile et al., 2013). Also, organic N is not stabilized and protected in sandy Sahel soil as well as in finer textured soils, thus organic N is more easily mineralized and taken up by plants or is lost from the system (Gentile et al., 2013). Total N does not increase with organic amendment compared to fertilizer because N uptake increases with greater base cation supply, better synchronization, and low N stabilization in the Sahel soil.

Total N is higher in the uncultivated and uncropped soil at both Sadore and Saria, despite receiving no N inputs, likely due to lack of N removal and export in crop harvest. Total N in the uncultivated is as high as in the high fertilizer treatment at Sadore, and higher but not significantly different than all fertility treatments except the high manure treatment at Saria. No till or reduced till was higher in total N than with tillage in other West African research

(Babalola and Opara-Nadi, 1993; Mando et al., 2005). Total N decreased over 25 years of continuous cultivation in Nigeria (Jaieyoba, 2003). Addition of 10000 kg ha^{-1} of manure improved total N at a long-term trial in Saria and improved total N further when reduced tillage practices were used because manure improved biological activity that was further stimulated through more intensive tillage (Mando et al., 2005). Adoption of reduced tillage systems and return of N in manure may help offset N losses, reducing fertilizer-N requirements for smallholder farmers. If reduced tillage is not feasible for farmers, then higher rates of manure or fertilizer are necessary to offset N outputs. To offset N losses, at Sadore, fertilizer at 30 kg N ha^{-1} is required, and at Saria, between 5000 and 40000 kg ha^{-1} of manure would be necessary. As well, continuous cereal cultivation may be impacting total N as well as tillage, because tillage had no effect on total N at a long-term trial under continuous maize in Nigeria, however, total N and soil C:N ratio declined regardless of tillage (Lal, 1997). Building up the soil N reserves with inorganic or organic amendment or through adopting minimum tillage is important to prevent high N losses with cropping and cultivation.

Contrary to total N, soil OC was not affected by cultivation at either Sadore or Saria. The effect of cultivation and cropping on SOC reported in other studies in West Africa varies. In some studies, OC was higher in no-till systems than conventional ploughing systems (Babalola and Opara-Nadi, 1993; Beare et al., 1994; Jaieyoba, 2003). Other research in semi-arid soils noted only slight increases in SOC of 100-200 kg ha^{-1} yr^{-1} with no-till (Lal, 1999). One reason for lower C with conventional ploughing in tropical soils is that OM is not protected from mineralization because tillage disturbs macroaggregate formation (Beare et al., 1994). There may be no difference at Sadore because SOC decomposition rates are already high due to sandy soil texture and year round high temperatures (Chivenge et al., 2007; Gentile et al., 2013). Continuous tillage may reduce OC accrual with OM amendment, as a long-term Sahel trial found that manure application improved SOC under hand hoeing, but not with ox ploughing, which disturbs soil more (Mando et al., 2005). Soil OC may be unaffected between the uncropped and cropped soils at Sadore and Saria, despite cultivation, because lower plant production in the fallow, which was seen in other research and led to lower SOC over the long-term (Farage et al., 2007). Total and available P were lowest in the uncultivated and uncropped soil that did not receive any inputs, which indicates the importance of fertility inputs for building up soil P, and that cultivation does not lead to P losses. Cultivation did not have an impact on soil P in other research in West Africa (Lal, 1997, Jaieyoba, 2003). As well, in Nigeria, untilled and unmulched soil was lower in available P compared to soil either tilled, mulched, or both, indicating residue mulching and not tillage was impacting available P (Henry and Chinedu, 2014). P is likely not affected by cultivation because it is more often cycled abiotically through organo-mineral interactions and is less impacted by stimulation of microbial activity than N (Juo and Franzluebbers, 2003; Knewtson et al., 2007; Fageria, 2009). Cultivation at Sadore and Saria did not influence OC and total and available P, however if feasible, adoption of no-till seems more likely to influence soil total N and reduce fertilizer-N requirements.

Cropping with legumes compared to continuous sorghum or millet did not have an impact on soil carbon at either site. This was also observed at other long-term sites in the Sahel comparing continuous millet or sorghum to legume intercropped or rotated millet or sorghum (Bationo and Ntare, 2000; Kouyate et al., 2012; Nakamura et al., 2012). Other studies showed an increase in soil C in mixed legume systems compared to continuous cereal attributed to greater C inputs from cowpea leaves dropping on the soil (Bationo and Buerkert, 2001). However, legume residues have a lower C:N that may stimulate soil C mineralization, where a higher C:N with cereal residues leads to N immobilization and C accrual (Powlson et al., 2001; Formowitz et al., 2009). Soil OC was not depleted with greater mineralization in the legume-cereal system in other research because biomass inputs were higher in the legume-cereal system (Yusuf et al., 2009). As well, clearing of crop residues, which occurs at both sites after harvest, may be reducing the impact of the different systems on C dynamics.

At Saria there was no significant difference between continuous sorghum and the sorghum-cowpea rotation in total N, but at Sadore, the millet-cowpea intercrop was higher in total N than the continuous millet system. Both the rotation and intercrop improved soil N fertility in some Sahel research, however, the rotation improved total N more than the intercrop because competition with cereal in the intercrop led to low legume yield and very low N inputs (Tiessen, 1988; Snapp et al., 1998). In other Sahel research, the millet-cowpea rotation was higher than the continuous system in mineral N (Bationo and Ntare, 2000), attributed to higher microbial activity in the rotation improving N availability (Keecy et al., 1989; Bagayoko et al., 2000b). Contrarily there was no difference in inorganic mineral N between continuous cereal and cereal in rotation with cowpea in other research (Bagayoko et al., 2000b). Along with different cropping systems, differences between sites may be because legumes are grown every year at Sadore and every other year at Saria, thus there is potential for more N fixation over time at Sadore. As well, N losses between growing seasons may be high, as less than 5% of total N in millet was derived from the previous cowpea crop in a ^{15}N-labelling study in the Sahel (Laberge et al., 2011). There may be greater N production in the intercrop overall, as cereal uptake of N occurs over the growing season in intercrops and stimulates greater legume N fixation in the intercrop (Eaglesham et al., 1981; Ndakidemi, 2006; Bationo et al., 2011). In general, mixed cropping may not improve soil N supplying power in the Sahel, but yearly legume N inputs through fixation and in-season N supply in the intercrop may improve crop N availability more than the rotation.

Continuous cereal systems are higher in total P at both Saria and Sadore, however, available P is higher in the continuous system only at Saria, with no difference between systems at Sadore. Total and available P may be higher with continuous cereal because legumes have higher P requirements than cereals due to N fixation (Hogh-Jensen et al., 2002; Knewtson et al., 2008). Available P was more depleted with intercropped bean and maize than maize alone in a pot experiment with clay rich, neutral pH soil (Li et al., 2008). In the same work, microbial P and organic P increased with legumes in the intercrop, indicating that under legume cropping, microbes were converting P to the organic form, making P less available. This mechanism may be at work in the rotation at Saria. As well, available P is higher overall at Saria than Sadore so legumes may be drawing P from the available pool at Saria, whereas available P levels are much lower at Sadore so legumes may be solubilizing unavailable P to meet their P demands. This would induce a change in total but not available P. Legumes, including cowpea, have the ability to solubilize less available forms of P, when P availability is low, by releasing organic acids and P solubilizing enzymes to the rhizosphere (Bekele et al., 1983; Ae et al., 1990; Jemo et al., 2006; Hassan et al., 2012). Incorporating legumes into the cropping system will lead to reduced soil total P because of higher P requirements, and may not have an impact on available P if P availability is low because of the ability of legumes to solubilize less available P.

4.6.3 Effect of ISFM treatments on soil C and N speciation and dynamics

Relative abundance of C and N functional groups in SOM at Saria and Sadore reveal the influence of fertility treatments, cropping systems, continuous cropping, and cultivation on C and

N dynamics. Amide-N, pyrrolic-N, and N-bonded aromatic abundances were impacted by organic matter input relative to fertilizer input at both sites, and cropping system also impacted amide abundance. Amides were higher in treatments with greater organic matter input, including the fert+NK+HM treatment at Saria, and R2F1M2 at Sadore. Amides were lower in treatments with fertilizer input and low or no organic input, including the fert+NK treatment at Saria, and R0F1M0 at Sadore. Treatments that were intermediate in amides at each site had balanced amounts of fertilizer and organic input. Amides are components of proteins and are broken down earlier in the degradation sequence because they are an easily used N source for microbes (Mengel et al., 1996, Vairavamurthy and Wang, 2002; Gillespie et al., 2014b; Albrecht et al., 2015). In the present work, amide abundance decreased when organic input decreased relative to fertilizer, which may be because fertilizer is stimulating microbial breakdown of easily accessible amide N. In other research, amide abundance was lower when soil N addition stimulated mineralization (Appel and Mengel, 1990). Furthermore, at Sadore the extra N addition in fertilized treatments stimulated greater amide breakdown. As well, amide N abundance is lower in the continuous than rotation for each treatment at Saria, and lower in the continuous than intercrop for the R2F2M2 treatment at Sadore. Amides are building up in the legume rotation in comparison to the continuous cereal treatments likely as a result of legume residues having a higher content of proteins and amino acids. The R2F2M2 may be the only treatment at Sadore where amides differ between cropping systems because the OM input is highest in this input and the C may be reducing net amide-N mineralization. Abundance of amides in treatments with greater organic input and in the mixed legume cropping systems may indicate these treatments lead to lower SOM degradation and/or that inputs and production of amides are greater in these treatments.

Along with amides, pyrrolics are also impacted by organic input in relation to fertilizer rate. As with amides, the fert+NK+HM treatment was highest and the fert+NK treatment was lowest in pyrrolics at Saria, and at Sadore all treatments were higher than the R0F1M0 treatment. At both sites, pyrrolics were lower in treatments where fertilizer input was greater than organic input. Pyrrolics are heterocyclic plant-derived compounds that are resistant to further degradation and that generally increase in abundance where more humification has taken place (Thorn and Mikita, 1992; Mengel et al., 1996; Mahieu et al., 2000; Vairavamurthy and Wang, 2002). Based on this, pyrrolics should remain in the soil even when N inputs are high because of their resistance to degradation. Research in Ontario, Canada found that pyrrolics were most abundant in high N fertility treatments, where N input stimulated microbial breakdown (Gillespie et al., 2014a). Only the fine soil fraction was measured in this research, which retains microbial degradation products, protecting them from further degradation (Grandy and Neff, 2008). The fine fraction is very small at Sadore and Saria, as soil is dominantly sand, which retains plant-derived compounds much better than those from microbes (Feller and Beare, 1997; Grandy et al., 2008). Pyrrolics may not be present in the treatments at Saria and Sadore with low or no OM and fertilizer application because there is no fine fraction to protect pyrrolics from further degradation when more N fertilizer is applied.

As with amides and pyrrolics, N-bonded aromatics are more abundant in treatments higher in organic matter inputs at both Sadore and Saria. At Saria, N-bonded aromatics are highest in the fert+NK+HM treatment and lowest in both the fertilizer alone and fert+NK, which was different from amides. At Sadore, N-bonded aromatics are highest in the R2F1M2 treatment and not different with the other treatments. Organic matter input is important for N-bonded aromatic abundance, however, fertilizer-N addition is not impacting abundance as for amides. N-bonded aromatics were also higher in treatments with greater organic input in other work (Asselman and Garnier, 2000; Gillespie et al., 2014a; Albrecht et al., 2015). N-bonded aromatics are formed through abiotic incorporation of N into the aromatic-C structure (Davidson et al. 2003; Palm and Sanchez 1991; Thorn and Mikita 2000). Aromatic-C is derived from humification of lignin, thus plant inputs are necessary for N-bonded aromatic formation. As well, treatments higher in organic input, the fert+NK+HM treatment at Saria and the R2F2M2 treatment at Sadore are higher in aromatics than all other treatments. Although the R2F2M2 treatment is not highest in N-bonded aromatics, it has the same organic input as the most abundant treatment, R2F1M2. Nitrite is a precursor for N-bonded aromatic formation, and in other research, nitrite was higher where nitrification was occurring and inorganic N was accumulating (Thorn and Mikita, 2000; Gillespie et al., 2011; Gillespie et al., 2014a). Nitrification rates and inorganic N levels were not determined in the current research, but may shed further light on N-bonded aromatic abundance. From these results, however, aromatic-C abundance, which is improved with organic input, is an important precursor for higher N-bonded aromatic levels.

At both research sites, aromatic C is higher where organic input is higher at both Sadore and Saria, and opposingly carbohydrate-C is lowest where fertilizer and organic matter input is highest. This is unexpected, because similar to amides, carbohydrates are more readily available and preferentially degraded, and carbohydrate content tends to decrease as humification proceeds (Sollins et al., 1996; Kögel-Knabner, 2000; Gillespie et al., 2011). Carbohydrate breakdown may expose lignins to breakdown (Baldock et al., 1992), but carbohydrates are also released from decomposing polysaccharides, which includes aromatic C (Gillespie et al., 2014a). As well, in other research, carbohydrates accumulated where soil was more degraded because carbon mineralization was not stimulated (Gillespie et al., 2011). Carbohydrates may increase in abundance as aromatic-C is broken down and then become stabilized in the degraded Sahel soil. Carbohydrate abundance in soils with less organic inputs indicates that soils at Sadore and Saria may be degraded and stabilizing more available C forms.

At both Saria and Sadore, cropping system and cultivation and cropping similarly impacted ketone and phenol abundance. At Saria, the uncultivated and uncropped soil was higher than the continuous cropped and cultivated soil in ketones and phenols, and the rotation was at a similar level to the uncropped soil and also higher than continuous cereal in ketones and phenols. At Sadore, the uncultivated and uncropped soil was also higher in ketones and phenols compared to the cropped and cultivated soil for each treatment in the continuous cereal system. Contrarily, there was no difference between the uncultivated and intercropped soil in ketones and phenols. These results indicate that continuous cereal cropping, and not long-term cultivation, is having an impact on ketone and phenol abundance. Presence of ketones indicates high microbial OM turnover because ketones are a product of microbial aromatic C metabolism (Gottschalk et al., 1986). The uncultivated soil is higher in aromatic C than cultivated at both sites, indicating depletion of aromatics in the cultivated soils is leading to abundance of ketones. Ketones are also an end product of microbial fatty-acid metabolism, thus their presence indicates greater microbial SOM turnover (Dent et al., 2004; Chan et al., 2009). Phenols are derived from plant materials and lignin, which is generally more resistant to breakdown than other organic groups (Palm and Sanchez, 1991; Grandy and Neff, 2008; Wickings et al., 2012; Gillespie et al., 2014b). Work has shown that phenol-C may break down if it is the least recalcitrant organic compound in the soil and conditions are suitable for mineralization (Gillespie et al., 2014b). Ketone and phenol abundance in the uncropped and mixed-cropping soils indicates OM degradation is higher in the continuous cereal system. Because ketones and phenols remain in the uncropped and mixed-cropping soils, there may be other more labile forms of C available for mineralization, indicating SOM is not being degraded to the same extent as the continuous system.

4.7. Conclusions

At the Saria and Sadore long-term research sites, the different long-term ISFM techniques had variable effects on soil chemical properties and fertility, and OM cycling. Crop residue at 2700 kg ha^{-1} at Sadore, and manure at 5000 kg ha^{-1} or higher at Saria were both able to buffer pH decline, but only the 40000 kg ha^{-1} manure rate improved SOC and CEC. Such a high manure rate may not be feasible for smallholder farmers due to lack of availability of large amounts of animal manure for field application, however, from the literature 6000 kg ha^{-1} of manure in the Sahel may improve SOC. Crop residue and manure will not improve P availability but will contribute to crop P nutrition if demand is not met with fertilizer application. Application of OM, especially manure, may increase N uptake through supplying other nutrients along with N that are not supplied with N and P fertilizers. Mixed cropping with legumes may lower soil pH because of addition of legume-fixed N to the soil that stimulates nitrification and increases soil acidity. P input seems more necessary when cropping with legumes due to their higher P demand, but in lower P soils such as Sadore, legumes also can likely access more recalcitrant P pools, improving P use efficiency. Long-term cultivation and continuous cereal cropping had no impact on most soil properties, but continuously cropped soil was lower in soil total N due to increased mineralization from cultivation, and additional N output in crop harvest compared to uncropped. Inorganic and organic fertilizer addition and reduced tillage practices that are feasible in the Sahel should be adopted to maintain or increase soil N fertility. Greater organic matter input, as well as mixed cropping with legumes increased abundance of more labile amide groups, which indicates lower levels of SOM degradation and greater supply of labile organic matter to fuel C and N turnover. Where organic input was higher, aromatic-C and subsequently N-bonded aromatic abundances increased and carbohydrate-C was lower perhaps corresponding with aromatic-C breakdown or due to stabilization of C in more degraded soils. The coarse soil texture at Sadore and Saria also affects soil C and N dynamics, as pyrrolic-C was not protected in soil aggregates when greater fertilizer-N addition favoured decomposition. Finally, soil under continuous cereal cropping was lower in ketones and phenols, indicating greater degree of OM turnover and less input of more available microbial substrate. Along with application of mineral fertilizer to meet nutrient requirements, increased organic matter input, adoption of reduced tillage practices, and integration of legumes with cereal cropping will buffer pH decline, reduce soil N requirements, maintain P, and improve soil C and N cycling, enhancing soil productivity in the Sahel, leading to improved food security and livelihoods for smallholders.

5. SYNTHESIS AND CONCLUSIONS

This research thesis investigated the long-term effect of a fertilizer rate typical of microdosing and other integrated soil fertility management practices on soil chemical properties and C and N dynamics in order to develop sustainable cropping systems in the Sahel. There are several important findings from this work that have implications for soil fertility management and policy needs in the Sahel. As well, from this research specific management recommendations can also be made to smallholders for sustainable management of their soil fertility. Finally, knowledge gaps and suggestions for future research can be identified from this work.

From the results of this thesis work, covered in detail in chapter 3, I conclude that inorganic fertilizer application is necessary to meet soil nutrient requirements, as demonstrated by the yield benefits and improvement of soil N and P concentration with addition of fertilizer. From the results, the reduced fertilizer rate does not inhibit soil functioning more than the recommended fertilizer rate. Yield response is greater between the unfertilized and reduced rate than between the reduced rate and recommended rate, and yield trend, which indicates potential decline over time, is no less negative for the reduced than recommended rate. Soil acidification and potential for depletion of nutrients not supplied in fertilizer is higher with the recommended rate than with the microdose rate. The organic C and N groups indicating lower levels of decomposition, including amide-N, pyrrolic-N, and aromatic-C, were depleted where there was higher inorganic fertilizer application, which indicates greater SOM breakdown with more fertilizer application. Soil fertility factors that explain in part the potential yield decline with fertilizer treatments include soil acidification, mining of nutrients other than N and P, and depletion of readily decomposable SOC. Although important for yield improvement, fertilizer application at either rate on its own is likely not the most appropriate approach for maintenance of soil fertility.

Another key finding outlined in chapter 4 is that applying organic matter along with fertilizer at as high a rate as feasible for smallholders is needed to maintain soil fertility. Crop residues at greater than 2700 kg ha^{-1} and at least 5000 kg ha^{-1} of manure will buffer pH decline from fertilizer N application. As well increasing manure and crop residue rates will further maintain or improve soil total P content. Manure may also add nutrients other than N and P that inorganic fertilizer treatments typically do not supply. Crop residue did not impact SOC, but manure applied at 6000 kg ha^{-1} or more will likely be effective in improving SOC concentration. In terms of SOM dynamics, at both sites soils with higher organic inputs were enriched in more labile amide-N species as well as plant derived aromatic-C, pyrrolic-C, and N-bonded aromatics indicating lower SOM decomposition levels and/or greater input of organic substrate that will fuel biological activity in the soil and nutrient cycling.

It is noteworthy that at both of the two sites, and especially at the Sadore site in Niger, SOC was very low and difficult to increase. The sandy soil texture does not effectively protect SOM from microbial degradation, and when combined with climatic factors that promote decomposition, only the 40000 kg ha^{-1} rate of manure resulted in significant increase in SOC. At both sites, C and N organic species, such as aromatic, ketone, phenol, and pyrrolic groups, that would normally be retained in the fine mineral soil fraction and in SOM aggregates were depleted with increased N application, likely due to microbial mineralization. Little can be done to change soil texture; nonetheless, organic matter rates and soil management practices should take into consideration the difficulty in sequestering organic carbon in these tropical soils compared to soils of temperate regions. Adoption of reduced tillage, if feasible in the Sahel, would both lower the amount of fertilizer N needed and increase nutrient use efficiency. Cropping with legumes may also improve soil N fertility, but the result of this practice was not consistent between the two sites.

The mixed cereal-legume system does appear to have several soil benefits compared to continuous cereal cropping. Although soil under mixed cropping was slightly lower in pH and total P, legumes improved P use efficiency because of their ability to solubilize organic P. As well, soil under mixed cropping was higher in amide groups than continuous cereal, suggesting lower SOM degradation or more input of readily available substrate. Long-term cereal monocropping had a significant impact on C and N speciation, as soil in the continuous system at each site was depleted in ketones and phenols compared to both the mixed cropping systems and the uncultivated and uncropped soil. Ketones and phenols are more recalcitrant organic C groups, and their absence in the continuous cereal system indicates that available substrate for microbial activity is low, as even difficult to degrade groups appear to be broken down by microbes. Mixed cropping of legumes and cereals may be more beneficial for SOM cycling.

There were some inherent limitations in the design of the long-term experiments that restricted their interpretative ability. At Sadore, a microdosed *rate* was used but fertilizer placement, another important component of microdosing, was not included in the design. At Saria, fertilizer treatments did not include a reduced and recommended rate, so only ISFM practices could be compared. A difficulty of doing this long-term research is that the experimental design at each site took place well before my time, thus I had to do the best with what I had been given. As well, I did not personally visit the research sites, and depended upon communication with the researchers that have experience at those sites for information. Yield records at Saria were incomplete because yield data was not recorded for each year and there was no yield data collected for some of the treatments included in the analysis. Yield trends for the different treatments, which would have added to the sustainability analysis, thus could not be calculated at Saria. Finally, controlled research plots may not accurately represent farmer conditions and management practices as they occur in the region.

Despite these limitations, there are many important soil fertility management recommendations and policy implications that arise from this research. This research is for naught if it cannot be broken down into practice recommendations applicable to smallholder farmers in the Sahel. From my work, I recommend that farmers not currently applying fertilizer adopt the microdosed rate to increase crop production at a lower risk than higher fertilizer rate through improving nutrient use efficiency. A suggested rate is 15 kg N ha^{-1} and 4.4 kg P ha^{-1}, which is 55 kg ha^{-1} CAN and 24 kg ha^{-1} SSP. If farmers are not able to apply this microdosed rate but can afford an even lower rate, this is better than not applying fertilizer at all. If farmers can only apply one type of fertilizer, P should be prioritized, as this nutrient was more limiting than N based on lower P than N uptake in response to manure at lower fertilizer rates, and because organic P was being solubilized from crop residues at lower fertilizer P rates. As production and income increases from fertilizer use, farmers should invest in higher rates of fertilizer to further improve production, but only with increased organic matter application. Farmers need to apply all crop residue and manure available to them to buffer pH from acidifying N fertilizer, add other nutrients beyond N and P, and improve SOC cycling. Farmers must apply organic matter at as high of rates as possible along with fertilizer to maintain soil pH, add macro and micronutrients other than N and P, and improve C and N cycling. If farmers cannot apply organic matter at all, it may not be sustainable to apply fertilizer long term. The amount of fertilizer applied relative to organic matter is important for C and N cycling, so farmers should not increase fertilizer rates if they cannot also increase organic matter rates. Retention of crop residues in the field should be made a priority by farmers, and capacity should be built to increase farmer access to livestock manure. If possible based on soil texture and moisture, farmers should adopt minimal tillage, tilling fewer times in a year or perhaps once in 2-5 years as suggested by Baudron et al. (2012), to reduce N losses from mineralization. Finally, farmers should incorporate legumes into cereal cropping systems as either an intercrop or rotation to improve SOC cycling and add more N to soil through fixation.

Key policy implications for adoption of the above recommendations to be possible are as follows. Smallholders need access to a dependable supply of inorganic fertilizer. Development of markets, infrastructure, and the private sector is needed. Increased access to financing and crop insurance is also likely needed to make fertilizer purchasing more affordable and less risky for smallholders. Feasible innovations to retain more crop residues in the field must also be developed. Substitutes for cooking fuel and building materials and methods to retain manure from crop residue grazing in the field, such as through corralling of animals are areas where innovation would be beneficial. When constraints of farmer access to inorganic and organic inputs are reduced, extension of these technologies is necessary to educate farmers on the benefits of small rates of inorganic fertilizer along with crop residue and manure. Finally, decision makers need to continue funding long-term research sites so that research to develop sustainable soil fertility management practices and cropping systems in the Sahel can continue. Continued funding is especially important with the looming challenge of climate change adaptation that is especially serious in West Africa.

Future research needs are an investigation of the macro- and micronutrient balances and availability, including nutrients other than N and P, with reduced and recommended rates of fertilizer. Research on the long-term impact of the microdosed placement as well as rate is also necessary. A complete nutrient balance study would be useful to understand nutrient dynamics in greater detail. Studying the feasibility of the different agronomic recommendations made in this research within the Sahelian smallholder context is also important. Research questions would be 1) How easily can farmers in the Sahel apply a reduced rate of fertilizer based on their access to fertilizer and financing; 2) How can it become feasible for farmers to leave crop residue in the field or gain access to more than 6000 kg ha^{-1} of manure; 3) How can it become viable for smallholders to adopt reduced tillage practices and/or incorporation of legumes in cropping systems. In general, as evidence of the benefits of soil fertility management techniques in the Sahel and other developing regions increases, efforts should shift from researching new practices to building capacity and increasing extension so that farmers can adopt and benefit from those practices. Both the development and distribution of soil fertility management tools is important, but actually putting the tools in the hands of farmers is what will improve livelihoods and sustainably improve food security in the Sahel for generations to come.

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APPENDIX A: SUPPLEMENTARY TABLES FROM SADORE RESEARCH SITE, NIGER

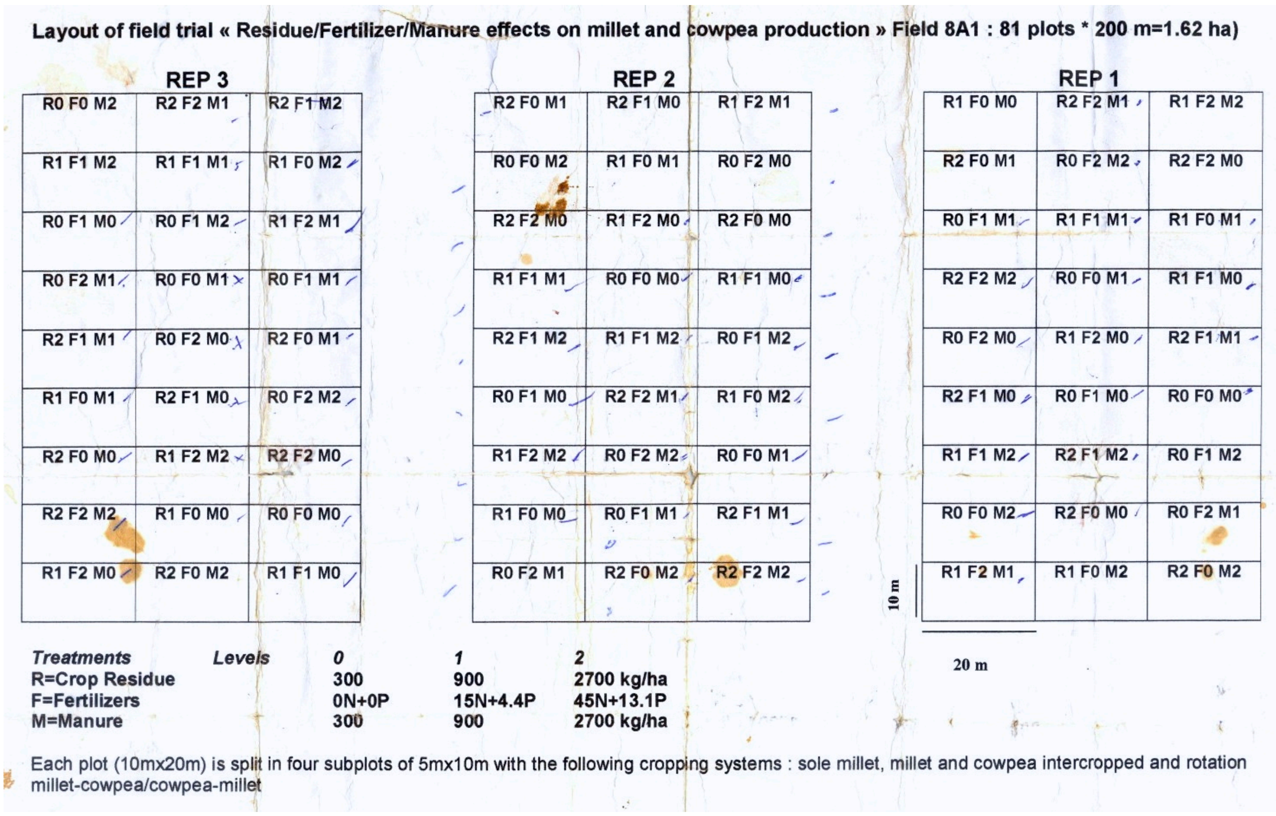

Fig. A.1. Sadore long-term research site field trial layout provided by ICRISAT researchers. Rotation of millet-cowpea/cowpea-millet was not included in current research.

Table A.1. Organic C, Total N, and C/N ratio of surface (0-20 cm) soil for C and N XANES samples at Sadore.

Treatment	OC	Total N	C:N
	mg kg^{-}		
R0F0M0	2100	74.1	28
R2F0M2	2200	91.1	24
R0F1M0	2600	92.5	28
R2F1M2	2600	105.6	25
R0F2M0	2700	117.1	23
R2F2M2	2600	138.0	19

R=residue, F=fertilizer, M=manure; F0=control, F1=reduced rate, F2=recommended rate; R0 and M0= low rate, R1 and M1= medium rate, R2 and M2=high rate

Table A.2. ANOVA for pH of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	**2**	**27.78**	**<.0001**
Fert	**2**	**77.32**	**<.0001**
Man	**2**	**11.91**	**<.0001**
System	**1**	**23.54**	**<.0001**
CR*Fert	**4**	**2.47**	**0.0488**
CR*Man	4	0.42	0.7915
CR*System	2	0.67	0.5115
Fert*Man	4	0.99	0.4163
Fert*System	2	1.50	0.2267
Man*System	2	1.28	0.2815
CR*Fert*Man	8	1.88	0.0701
CR*Fert*System	4	1.73	0.1482
Fert*Man*System	**4**	**3.19**	**0.0161**
CR*Fert*Man*System	12	0.88	0.5692

CR = crop residue, Fert = fertilizer, Man = manure, * denotes interaction of treatment types. Applies to Tables A.4. through A.9.

Table A.3. ANOVA for EC of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	2	1.57	0.2120
Fert	2	0.85	0.4301
Man	2	2.34	0.1014
System	1	1.35	0.2485
CR*Fert	4	0.17	0.9533
CR*Man	4	1.31	0.2701
CR*System	2	2.41	0.0943
Fert*Man	4	0.52	0.7236
Fert*System	2	0.64	0.5304
Man*System	2	3.05	0.0514
CR*Fert*Man	8	1.06	0.3947
CR*Fert*System	4	0.79	0.5354
Fert*Man*System	4	0.76	0.5510
CR*Fert*Man*System	12	0.78	0.6685

Table A.4. ANOVA for CEC of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	2	0.83	0.4404
Fert	2	0.92	0.4036
Man	2	2.46	0.0905
System	1	55.93	**<.0001**
CR*Fert	4	0.25	0.9105
CR*Man	4	0.42	0.7944
CR*System	2	0.23	0.7987
Fert*Man	4	0.91	0.4589
Fert*System	2	1.42	0.2473
Man*System	2	1.09	0.3395
CR*Fert*Man	8	2.88	**0.0060**
CR*Fert*System	4	0.51	0.7299
Fert*Man*System	4	1.20	0.3134
CR*Fert*Man*System	12	1.01	0.4431

Table A.5. ANOVA for OC of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	**2**	**11.48**	**<.0001**
Fert	**2**	**6.76**	**0.0017**
Man	**2**	**5.59**	**0.0049**
System	1	0.39	0.5323
CR*Fert	4	0.54	0.7088
CR*Man	4	1.33	0.2634
CR*System	2	0.40	0.6732
Fert*Man	4	2.04	0.0945
Fert*System	2	0.17	0.8475
Man*System	**2**	**12.18**	**<.0001**
CR*Fert*Man	**8**	**5.76**	**<.0001**
CR*Fert*System	4	1.79	0.1360
Fert*Man*System	4	0.70	0.5932
CR*Fert*Man*System	12	1.72	0.0729

Table A.6. ANOVA for Total P of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	**2**	**7.13**	**0.0120**
Fert	**2**	**27.89**	**<.0001**
Man	**2**	**90.55**	**<.0001**
System	**1**	**173.82**	**<.0001**
CR*Fert	**4**	**4.02**	**0.0045**
CR*Man	4	1.10	0.3601
CR*System	**2**	**4.43**	**0.0141**
Fert*Man	**4**	**3.25**	**0.0146**
Fert*System	**2**	**4.16**	**0.0182**
Man*System	**2**	**35.15**	**<.0001**
CR*Fert*Man	**8**	**4.10**	**0.0003**
CR*Fert*System	4	1.50	0.2064
Fert*Man*System	4	1.58	0.1851
CR*Fert*Man*System	**12**	**2.63**	**0.0040**

Table A.7. ANOVA for Available P of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	2	2.35	0.1000
Fert	**2**	**99.32**	**<.0001**
Man	2	3.06	0.0511
System	1	0.21	0.6475
CR*Fert	4	1.86	0.1235
CR*Man	4	0.69	0.6006
CR*System	2	0.35	0.7046
Fert*Man	**4**	**10.19**	**<.0001**
Fert*System	**2**	**25.34**	**<.0001**
Man*System	2	1.31	0.2749
CR*Fert*Man	8	0.42	0.9092
CR*Fert*System	4	1.43	0.2300
Fert*Man*System	4	1.46	0.2196
CR*Fert*Man*System	12	0.41	0.9588

Table A.8. ANOVA for Total N of surface (0-20cm) soil at Sadore.

Source	df	F value	Pr > F
CR	**2**	**3.21**	**0.0440**
Fert	**2**	**60.09**	**<.0001**
Man	**2**	**37.17**	**<.0001**
System	**1**	**33.62**	**<.0001**
CR*Fert	4	1.94	0.1087
CR*Man	4	2.09	0.0871
CR*System	2	1.92	0.1511
Fert*Man	**4**	**2.52**	**0.0454**
Fert*System	**2**	**18.59**	**<.0001**
Man*System	**2**	**47.82**	**<.0001**
CR*Fert*Man	8	1.64	0.1220
CR*Fert*System	4	1.94	0.1086
Fert*Man*System	4	1.98	0.1030
CR*Fert*Man*System	12	1.42	0.1671

Table A.9. Organic Carbon for crop residue, fertilizer and manure application in surface soil (0-20 cm) at Sadore.

			Organic Carbon	
Fertilizer Rate	Crop residue Rate	Manure Rate	%	
Low	Low	Low	0.20	cd
		Medium	0.20	d
		High	0.28	ab
	Medium	Low	0.22	bcd
		Medium	0.27	abcd
		High	0.24	abcd
	High	Low	0.27	abcd
		Medium	0.25	abcd
		High	0.25	abcd
Medium	Low	Low	0.27	abcd
		Medium	0.24	abcd
		High	0.25	abcd
	Medium	Low	0.20	d
		Medium	0.24	abcd
		High	0.31	a
	High	Low	0.26	abcd
		Medium	0.29	ab
		High	0.29	ab
High	Low	Low	0.25	abcd
		Medium	0.25	abcd
		High	0.24	abcd
	Medium	Low	0.28	ab
		Medium	0.28	abc
		High	0.24	abcd
	High	Low	0.27	abcd
		Medium	0.28	ab
		High	0.30	a

APPENDIX B: ANOVA TABLES FROM SARIA RESEARCH SITE, BURKINA FASO

Table B.1. ANOVA for pH of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**92.52**	**<.0001**
Rotation	1	3.75	0.0576
Trt*Rotation	5	1.03	0.4067

Table B.2. ANOVA for EC of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**13.61**	**<.0001**
Rotation	1	0.69	0.4078
Trt*Rotation	5	0.54	0.7484

Table B.3. ANOVA for CEC of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**62.16**	**<.0001**
Rotation	1	2.85	0.0968
Trt*Rotation	5	0.82	0.5388

Table B.4. ANOVA for OC of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**5.40**	**0.0004**
Rotation	1	1.57	0.2148
Trt*Rotation	5	1.85	0.1173

Table B.5. ANOVA for total P of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**30.56**	**<.0001**
Rotation	**1**	**19.94**	**<.0001**
Trt*Rotation	5	1.02	0.4135

Table B.6. ANOVA for available P of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	**5**	**53.72**	**<.0001**
Rotation	**1**	**15.32**	**0.0002**
Trt*Rotation	5	1.18	0.3316

Table B.7. ANOVA for total N of surface (0-20cm) soil at Saria.

Source	df	F Value	Pr > F
Treatment	5	2.15	0.0715
Rotation	1	1.52	0.2224
Trt*Rotation	5	1.52	0.1978