INTEGRATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM IN SOIL FERTILIY MANAGEMENT IN MALI

BY

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A thesis presented to the Department of Crop and Soil Sciences, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, in partial fulfilment of the requirements of the degree of

Doctor of Phylosophy

in Soil Science

BY

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(BSc. GEOGRAPHY, MSc. NATURAL RESOURCES MANAGEMENT)

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DECLARATION

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

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Signature Date

ABSTRACT

A study was carried out using remote sensing and GIS to support decision making for appropriate land management practices aimed at improving the soil fertility status as well as millet and sorghum yield on the acid soils at Siguidolo in Mali. Aster image was used to identify elevation levels. Landsat image and visual interpretation were used to delineate soil units and to perform stratified random sampling. Quick bird image was utilized to assess vegetation concentration with normalized difference vegetation index (NDVI). On-site field measurements and surveys were carried out using GPS for ground verification and soil sampling. Laboratory analysis of soil samples was performed to generate values for mapping the spatial distribution of soil clay, sand and silt content as well as soil pH, C, N, P and K content using ArcGIS. Soil textural triangle was used to identify the soil textural classes. Twenty five soils units were delineated comprising loam (78.21 ha), loamy sand (68.99 ha) and sandy loam (689.06 ha). The pH of the soils ranged from moderately acid (5.5-6.1) to very strongly acid (4.7-5.1). The organic carbon and NPK content of the soils were very low. Soil fertility was therefore very low. The vegetation cover consisted of bare soil (278.26 ha), grassland with scattered trees (451.1 ha) and woodland with grass cover (148.93 ha). The cropping system was mainly cereal-based cultivated either sole or intercrop. Continuous cereal production is predominant but legume-cereal rotation has significantly increased over the three year period of 2011 to 2013. To facilitate the recommendation of improved land management for the Siguidolo area, a factorial experiment comprising two tillage practices (ridge and hoe tillage) and five soil amendments (No amendment; sole Profeba; Profeba + Urea; Profeba + Urea + TPR; and Profeba + Urea + Lime), arranged in a randomized complete block design with three replications was set up. The results were analysed by Analysis of variance using Lsd (0.05). Soil pH increased by 10-12% and 7.2 to 8.8% under ridge and hoe tillage respectively. The soil amendments generally increased the initial pH of 4.78 in the order of $P_4 > P_3 > P_2 > P_1 > P_0$ with a range of 4.80 to 5.56. Soil organic carbon was enhanced under ridge and hoe tillage with their respective increases being 18-23% and 11 to 22% over the control. Soil amendments also increased SOC in the same order as pH. Ridge and hoe tillage increased available phosphorus by 0.9 to 37% and 24% respectively under millet and sorghum. Available phosphorus as affected by soil amendments ranked as $P_3 > P_4 > P_2 > P_1 > P_0$ under sorghum with a range of 1.65 to 4.01 mg kg^{-1}. The range under millet was 1.39 to 2.47 mg kg^{-1}. Tillage x soil amendment significantly ($P<0.05$) affected available P under sorghum in 2014 with P_3 x R_1 and P_2 x R_1 recorded higher values. There was a general decline in total N and exchangeable K. The grain yield of sorghum and millet was consistently higher under ridge tillage than hoe tillage. The Profeba compost + Urea and Profeba compost + Urea + TPR were the most promising soil amendments for sustainable crop production in the Siguidolo area.

DEDICATION

To

This Thesis is dedicated to my dad Blonda dit Alou, my mum Batoma BOUARE, my husband Bocar dit Sire BA, and my Children Oumar and Nouhoum BA

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CHAPTER ONE

1.0 INTRODUCTION

1.1 The problem of soil fertility decline

The challenge for agriculture in Africa, particularly Mali, is to meet the increasing demand for food in a sustainable way. Declining soil fertility and mismanagement of plant nutrients have made this task difficult (Petter *et al*., 2000). There is also a growing consensus that improvement of soil fertility and the conservation of soil and water resources are the starting points for agricultural development in West Africa (Stoorvogel *et al*., 1990; Bationo *et al*., 1997). This consensus is supported by mounting evidence that traditional soil, water and nutrient management practices, based on mining soil nutrients are not enough to attain the 4% annual growth rate in agricultural production needed to meet the food requirements of the rapidly growing population (Loeffen, 2008).

1.2 The status of soil fertility decline in Mali

Low inherent soil fertility and decline are a widespread problem in Mali which is on the increase and would require spatially oriented solutions to make any significant impact.

As a degradation process, soil fertility decline affected 4% and 26% of the agricultural land area of Mali in 1952 and 1975 respectively. In the 1990s, it led to 10-60 % losses in soil nutrients (Kieft *et al*., 1994). Estimates by Stoorvogel *et al*. (1990) and Van der Pol (1992) indicated that Malian soils lost 8, 2 and 8 kg/ha of Nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) respectively during the 1983 cropping season. The respective projected losses for the year 2000 were 11, 6 and 12 kg/ha/year.

In the Segou area, encompassing Siguidolo, in Mali, Dembele *et al.* (2000), reported a negative nutrient balance for N, P_2O_5 and K_2O. The N balance was -14 kg/ha/year in village compound fields and -32 kg/ ha/ year in the bush farms.

Soil nutrient depletion has been found to be a serious problem for crop production and food security in the Siguidolo area (Doumbia *et al*., 2009) which, incidentally, is the current study site. The main problem is soil acidity. In addition to sandy textures, low water retention capacity and soil carbon content (Doumbia, *et al.,* 2009) the complex impact of soil acidity includes nutrient deficiencies (P, Ca, and Mg), the presence of phytotoxic nutrients (Al and Mn) and reduced crop growth and yield (Zhuo *et al.,* 2009a). Efforts to assess the magnitude and spatial extent of the soil fertility problem in this area, as done in this study, would contribute significantly to the development of strategies and interventions to address the low fertility problem for improved crop yield.

1.3 The cause of soil fertility decline in Mali

Most of Mali's soils are affected by natural low fertility (Jens *et al.,* 2007). The use of organic and inorganic fertilizer lower than recommended rate (Kieft *et al*., 1994) increases the initial low fertility. In 2002 the average fertilizer used per hectare was only 9 kg/ha (Jens *et al*., 2007). Also, population growth and the scarcity of agricultural land have resulted in decrease in the length of fallow period. This is crucial because with no fallowing period there is no fertility-enhancing impact on the soil (Hoefsloot *et al*., 1993; Jens e*t al.,* 2007).

The application of manure, household waste and mulch are among ways to improve soil fertility (Samake, 2003). The main constraint to these practices is that small scale farm households do not own enough cattle to facilitate manure collection (De

Ridder *et al.,* 1990; Dembele, 2000). The intensified pressure on the land has also reduced herds, because traditional grazing lands have been turned into farmlands. People have also sold their animals because farmers are no longer able to feed themselves from their cropland, so they manage the famine time by selling their animals (Samake, 2003). One consequence of the reduction in animals is the unavailability of animal manure in adequate quantities. Mulching is not used on smallholder farms because of the competitive demand for crop residues for human needs and animal feed (Samake, 2003). In Mali, Camara (1996) indicated that due to high human demand for crop residues, less than 10% is buried to return nutrient removed from the soil.

Erosion risk is also very high in tropical regions due to the high intensity of rainfall. According to Roose (1981), a significant amount of runoff is generated on both cultivated soil and under herbaceous vegetation. Superficial crusts, frequently formed on unprotected soil due to raindrop impact, reduce soil infiltrability and enhance runoff and soil and nutrient losses. Erosion control on arable lands is therefore a major pathway for reducing soil fertility decline (Casenave *et al.,* 1989).

1.4 Past efforts in addressing the soil fertility decline problem in Mali

The adverse impacts of soil fertility degradation have attracted several studies with the view to addressing the problem. These include water harvesting using ridge tillage, erosion control measures, composting, and development of germplasm for the agro ecology (Gigou *et al*., 2006 and Doumbia *et al*., 2009). Despite these efforts crop production still remains low.

Studies directed at integrating current new tools of remote sensing and GIS in soil fertility management activities for developing spatially oriented solutions to the soil fertility problems are conspicuously absent in Mali.

The search for practicable solutions, therefore, continues to be relevant. The fundamental solution to the soil fertility problem in the study area is to correct soil acidity. This will involve the use of available and affordable liming materials by the many scattered smallholder farms. These include the application of agricultural lime to stimulate crop growth by eliminating aluminium and iron toxicities and increasing the availability of P and other plant nutrients such as calcium and nitrogen (Adams, 1984 and Black, 1993).

Tilemsi Phosphate Rock (TPR), an inorganic material, has been used to address soil acidity (Julio, 1999). An economic evaluation of TPR under farmers' operating conditions for three cropping rotations clearly indicated that the direct application of TPR could be profitable than the recommended imported P fertilizers (Bationo *et al*., 1997).

Other workers have shown that organic residues from green and animal manures can increase pH of acid soils and improve soil fertility (Hue, 1992; Warren *et al.*, 1993; O'Hallorans *et al*., 1997). The effect of animal manure on soil pH may persist over several years (Klebonye, 2011). Organic material like Profeba, an improved compost, is a promising liming source which could be used to reduce Al toxicity and improve P availability and soil fertility in Mali but has not been tested (Doumbia, *et al*. 2009).

1.5 The need for integrating Remote Sensing and Geographic Information System (GIS) with conventional soil fertility assessments

Considering that Mali's agriculture is dominated by scattered smallholder farms, a spatial assessment of the fertility problem by GIS would be a prerequisite for effective nutrient management for sustainable agricultural production. Besides, timely up to date and accurate information, such spatial data would indicate the variability, distribution and the degree of soil nutrient depletion to enhance decision-making.

In spite of this, such information is currently not available for the design of sustainable soil nutrient management. This may be due to the fact that the use of traditional methods for mapping and estimating potential risk areas is relatively costly and time consuming and is subject to a variety of errors. However, recent advances in computing power and the increasing availability of remote sensing data have made it possible in using GIS to address a wide range of such environmental issues and questions. According to Lobell, (2010), mapping and monitoring the occurrence of soil degradation will be an important component of successful land management in the 21st century. The extent of land degradation in Mali makes this assertion more relevant. Remote sensing, with its unique ability to measure across space and time, will be an increasingly indispensible tool not only for assessing soil degradation (Lobell, 2010), but for facilitating the development of informed choices of appropriate technologies to address, the problem. The unique power that GIS provides to the users to collect, process and manage information makes it one of the best current tools that can facilitate appropriate decision-making in the sustainable management of soil fertility, crop production and food security.

In soil fertility management, the integration of remote sensing and GIS with conventional soil fertility assessments has several benefits. These include, among others, cost effective and efficient use and coverage of soil fertility recommendations generated from the many scattered research activities in a given agro-ecological zone.

However, because these new tools are currently not in use for soil fertility management, these benefits have and continue to elude the efforts so far made towards finding lasting solution to the soil fertility problems in Mali. This gap has opened the integration of remote sensing and GIS into soil management activities as a new area of research. In this respect, this study recognizes the integration of these new tools into soil fertility management as the way forward for Soil Scientists and Agronomist towards developing effective soil fertility decline remediation strategies to avert the food insecurity problem in Mali and other sahelian countries.

Developing a notion of what is driving the soil fertility degradation process would require point measurements of soil fertility components and spatially distributed information generated by satellite remote sensing and GIS showing the relative differences in the magnitude of the fertility problem. Once identified Sustainable Land Management (SLM) technologies could be spatially applied to deal with the constraints. Where adequate point data is not available, as in the case of the study site, there would be the need for extensive testing of promising technologies possibly on benchmark soils to facilitate the provision of spatial solutions to the soil fertility problem through interpolation.

In this context, Profeba, an improved compost, has been identified as a promising soil amendment in contributing to the solution of Mali's soil fertility problems (Doumbia *et al.,* 2009). Since Profeba as sole and in combination with other soil amendments and management practices have not received much research attention, it is envisaged that such a study would be worthwhile in revealing its potential fertilizer and liming value, as well as its cost effectiveness in the management of the acid soils of Mali. This is particularly relevant considering the high cost of agricultural lime usage and its slower reaction with soil colloids than manure and compost (Brady, 1999). The outcome of such a study, when adequately replicated in the study site could facilitate the provision of spatially oriented recommendations through the use of GIS. These concerns informed the choice of the topic and the objectives of the study.

1.6 OBJECTVES

The overall objective of this study was to use remote sensing and Geographic Information System integratively with conventional methods of soil fertility assessment to facilitate decision making in the choice of sustainable land management practices.

The specific objectives were to:

i. Use remote sensing, GIS and GPS data to delineate soil units, vegetation cover and cropping systems at Siguidolo
ii. Map the different levels of pH, N, P, K and C using the results from laboratory analysis of soil samples and GPS data in a GIS domain.
iii. Assess the impact of Profeba compost when applied sole and in combination with Tilemsi Phosphate Rock (TPR), lime and urea under different tillage practices on some selected soil parameters (pH, N, P, K, and C) and crop yield.
iv. Recommend the most appropriate and cost effective land management practices for sustainable millet and sorghum production for replication.

1.7 Hypotheses

i. Remote sensing and GIS would improve decision making in the choice of sustainable land management in Siguidolo

ii. The application of Profeba compost would improve the fertility and productivity of acid soils.

iii. The combined use of Profeba and different tillage practices would improve millet and sorghum yield

iv. The use of Profeba is cost effective

CHAPITER TWO

2.0 LITERATURE REVIEW

2.1 Soil Degradation

Soil degradation is the decline in soil quality caused by its improper use, usually for agricultural, pastoral, industrial and urban purposes (Johns, 2015). Soil quality, as defined by Doran *et al*. (1994), is the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environment quality and promote plant and animal health.

Soil degradation is a serious global environmental problem, encompassing the physical, chemical and biological deterioration of soil. These include, decline in soil fertility, deterioration of soil structure, erosion, loss of organic matter, adverse changes in salinity or alkalinity and the effect of toxic chemicals, pollutants and excessive flooding (Zhuo *et al.*, 2009a). Among these, this study focuses on soil fertility decline and acidity.

The literature on soil fertility is therefore reviewed with particular emphasis on soil acidity, which is considered the major driver of the soil fertility problem and constraint to sustainable production in Mali. The highlights of the review include causes of soil acidity; its influencing factors and impact on nutrient availability and uptake by crops; the relative benefits of different tillage practices in creating favourable conditions for crop growth and yield; the use of liming, particularly from local sources as well as integrated nutrient management involving the combined use of agronomic and mineral sources of nutrients.

The need to integrate remote sensing and geographic information system (GIS) into soil fertility management equally necessitated a thorough review of Remote sensing and GIS, their integration and use in mapping delineated soil units and soil fertility components to show their spatial distribution and hot spots. The review finally revealed work done and knowledge gaps in the subject matter areas of the study to form the basis of the objectives of this study.

2.1.1 Soil acidity

Soil acidity, a major property associated with the soil fertility decline, is currently the main challenge for farmers and researchers in Siguidolo. It is attributed mainly to the abundance of hydrogen, aluminium and manganese cations in soil at levels that interfere with normal plant growth (Osundwa *et al*., 2013). Soil acidity may be attributed to the composition of the parent material from which the soils were formed, the fertilizers used and the type of farming system.

2.1.1.1 Factors affecting soil acidity

Soil pH decreases faster in sandy soils. These soils have a lower cation exchange capacity and so are less able to retain nutrients against leaching. They also have a lower water holding capacity, resulting in greater drainage and leaching soluble nutrient including bases. Clay soils have a greater cation exchange capacity and a greater water holding capacity and therefore can buffer against acidification (Arthur, 2010).

Nitrogen fertilizers on the other hand, have a greater acidifying effect on soils than other fertilizers. Two processes are involved. First, commonly used, nitrogen fertilizers contain ammonium nitrogen. Soil bacteria convert ammonium to nitrate through a biochemical process called nitrification. The second acidifying effect comes from nitrate that is not taken up by the growing crop (Spies *et al*., 2007). If the NH_4^+ is taken up by the plant before nitrification takes place and in quantities greater than the accompanying anion, soil acidity will result from proton release from roots. However, nitrification takes place rapidly in most soils so that the window of opportunity for NH_4^+ plays a role in soil acidification, and theoretically two moles of H^+ are released per mole of NH_4^+ converted to nitrate (Jolley *et al*., 1977). The study done by Lungu *et al.* (2008) have shown that long-term annual application of urea resulted in soil acidification and decreases in exchangeable Ca and Mg, especially if these were already low in the soil.

Soil Organic Matter (SOM) may also contribute to soil acidity. As microorganisms decompose soil organic matter (O.M), they release carbon dioxide that quickly reacts with water (H_2O) to produce H^+ and HCO_3^-. Decomposition of organic residues and root respiration increases carbon dioxide in soil air to about ten times the atmospheric carbon dioxide, thus, acidity produced from carbon dioxide in soil air is greater than that produced in the atmosphere (Bareeleng, 2011). In addition, microorganisms produce organic acids. Soil OM content varies with the environment, vegetation and soil, thus its contribution to soil acidity varies accordingly. Mineral soils containing large amounts of OM and organic acids contribute significantly to soil acidity (Havlin *et al.*, 2005). Decaying of organic matter produces hydrogen which is responsible for acidity.

Harvesting of crops has its effect on soil acidity development because crops absorb the exchangeable bases, as cations, for their nutrition. When these crops are harvested from the field, some of the basic material responsible for counteracting the acidity developed by other processes is lost, resulting in increased soil acidity. The amount of these nutrients removed by cropping depends on a) the crop grown, b) part of crop harvested and c) stage of growth at harvest (Spies *et al*., 2007).

Rainfall is also implicated in the acidity problem. Excessive rainfall is an effective agent for removing basic cations over long periods. Rainfall is the most effective in causing soil acidity through leaching of bases. Sandy soils are often the first to become acidic because water percolates rapidly, and sandy soils contain only a small reservoir of bases (buffer capacity) due to low clay and organic matter contents. Soils can however become acid even in the absence of crop removal or fertilizer application, (Spies *et al.*, 2007).

2.1.1.2 Effect of soil acidity on crop response

Soil pH affects crops in many ways mostly indirectly, through its influence on chemical factors and biological processes. The chemical factors include aluminium (Al) toxicity, calcium (Ca) and phosphorus (P) and magnesium (Mg) deficiencies (Uchida *et al.*, 2000). Optimum nutrient uptake by most crops occurs at a soil pH near 7.0. The availability of nutrients such as nitrogen, phosphorus and potassium is generally reduced as soil pH decreases. Phosphorus is particularly sensitive to pH and can become a limiting nutrient in strongly acid soils. Thus, reduced fertilizer use efficiency and crop performance can be expected when soil acidity is not properly managed (McFarland *et al.*, 2005).

2.2 Soil Tillage

The most fundamental operation in agricultural production is tillage. It aims to create a soil environment favourable to plant growth (Klute, 1982). Definitions of tillage vary but as summarized by Prihar (1990) as the physical or mechanical manipulation of soil to modify soil conditions for the purpose of crop production by providing a conducive environment for seed germination and root development, suppressing weed, controlling soil erosion, increasing infiltration and reducing evaporation of soil moisture.

Soil manipulation can change the fertility status markedly and the changes may be manifested in good or poor performance of crops (Ohiri *et al.,* 1990). Tillage operations loosen, granulate, crush or compact soil structure, changing soil properties such as bulk density, pore size distribution and composition of the atmosphere that affect plant growth. Appropriate tillage practices are those that avoid the degradation of soil properties but maintain crop yields as well as ecosystem stability (Lal, 1985a and Geenland, 1981). Conservation tillage provides the best opportunity for halting degradation and for restoring and improving soil productivity (Parr *et al*., 1990). In recent years interest in conservation tillage has increased in response to the need to limit erosion and promote water conservation (Hulugalle *et al*., 1986; Unger *et al*., 1988). The following tillage systems are the most common practised by farmers.

2.2.1 Types of tillage

The no-till system is a specialized type of conservation tillage consisting of a one-pass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed (Parr *et al*., 1990). The surface residues of such a system are of critical importance for soil and water conservation. Weed control is generally achieved with herbicides or in some cases with crop rotation. According to Lal (1983), no-tillage systems eliminates all replanting mechanical seedbed preparation except for the opening of a narrow (2-3 cm wide) strip or small hole in the ground for seed placement to ensure adequate seed/soil contact. The entire soil surface is covered by crop residue mulch or killed sod.

The no-till fallow is a type of no-tillage system which is used in dryland areas in the USA. No-till fallow has been most successful in summer rainfall areas (Parr *et al.*, 1990). A major goal of fallowing is to recharge the soil profile with water so that the risk of failure for the next crop is greatly reduced (Unger et *al.*, 1988). According to Parr *et al.* (1990), the potential benefits of no-till fallow, compared with other tillage systems, are more effective control of soil erosion, increased water storage, lower energy costs per unit of production and higher grain yields. A major disadvantage of no-till fallow (sometimes referred to as chemical fallow) is its heavy use of herbicides for weed control.

Mulch tillage techniques are based on the principle of causing least soil disturbance and leaving the maximum of crop residue on the soil surface and at the same time obtaining a quick germination, and adequate stand and a satisfactory yield (Lal 1986b). Lal (1986b) further reported that a chisel plough can be used in the previously shredded crop residue to break open any hard crust or hard pan in the soil. Care should be taken not to incorporate any crop residues into the soil. The use of live mulch and crop residue *in situ* involves special mulch tillage techniques or practices. *In situ* mulch, formed from the residue of a dead or chemically killed cover crop left in place (Wilson, 1978a, b), is generally becoming an integral component of mulch tillage techniques.

Mulches help reduce soil moisture loss through evaporation, improve soil water holding capacity and soil's physical structure, accelerate soil biological activity, aeration, and drainage over time (Mando, 2005). It protects plant roots from extreme temperatures, helps control weed germination and growth. In Kenya, mulching was found to increase soil humus, provide nutrients and energy to soil organisms, suppress weed growth and Mulches improved crop yield (ISA, 2011).

The concept of strip or zonal tillage is described by the seedbed divided into a seedling zone and a soil management zone. The seedling zone (5 to 10 cm wide) Lal (1983) is mechanically tilled to optimize the soil and micro-climate environment for germination and seedling establishment. The inter row zone is left undisturbed and protected by mulch. Strip tillage can also be achieved by chiselling in the row zone to assist water infiltration and root proliferation.

The most noted advantage is the reduction in soil erosion and runoff, and consequently, nutrient loss (Angle, 1985). Partially buried residue increases the roughness of the soil surface and provides an increased opportunity for water to enter the soil profile (Fisher *et al.*, 1973). This increased roughness reduces the factors involved with soil displacement and movement by buffering the energy associated with raindrop impact and slowing the speed of water movement across the soil surface (Stone *et al.*, 1996). The biomass attained from the cover crop forms small dams, which allows surface water to pond and suspended soil particles to settle out of solution, thus reducing the transport of detached soil particles in the cropped field.

This system covers other tillage and cultivation systems not covered above but meets the 30% residue requirement (Laryea *et al.*, 1991). In Africa, the term minimum tillage is not always employed with the same meaning as in temperate countries, and may also be used differently in the different contexts of shifting cultivation (still the dominant system in most of Africa) and mechanized agriculture (Ahn *et al.*, 1990).

Hoes in different shapes and weights are the tools used for hand-tillage operation, unless contract ploughing with animals or tractors is used. Tillage depth and intensity with hand tools is very limited, but as it also leaves the soil exposed, it equally leads to soil degradation and erosion (FAO, 2014). It may even the create compaction zones (hoe-pans). Tillage tools might still be necessary for some specialized operations even under conservation agriculture, such as reshaping beds or maintaining irrigation ditches. However, under conservation agriculture there is no general tillage any more and farmers use direct seeding. With this the main bottleneck of labour availability for land preparation is eliminated (FAO, 2014), hoeing for land preparation is eliminated with conservation agriculture (CA). These reduce the major labour constraints in the cropping season (FAO, 2014). Hoeing with hand-held implements during plot preparation, sowing, and weeding are an important agent of tillage erosion on sloping lands in developing countries (Alan, 2012). Zhang *et al*. (2009) suggested that non-overturning hoeing tillage largely diminishes soil downslope translocation and results in a significant reduction in tillage erosion.

Ridge tillage sometimes called contour furrows, contour ridges or micro watersheds, are used for crop production. Ridges follow the contour at a spacing of usually 1 to 2 meters. Runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges. Crops are planted on both sides of the furrow (Jack, 2012). The yield of runoff from the very short catchment lengths is extremely efficient and when designed and constructed correctly there should be no loss of runoff out of the system. Another advantage is an even crop growth due to the fact that each plant has approximately the same contributing catchment area (Jack, 2012).

Since the contour ridge technique implies a new tillage and planting method compared with conventional cultivation, farmers may be initially reluctant to accept it (Jack, 2012). Demonstration and motivation are therefore very important to enhance its acceptance or adoption. On the other hand, it is one of the simplest and cheapest methods of water harvesting. It can be implemented by the farmer using a hoe, at no or little extra cost. External support is reduced to a minimum. Alternatively it can be mechanized and a variety of implements can be used. When used on a farmer own land, the system does not create any conflicts of interest between the implementer and the beneficiary (Jack, 2012).

2.2.2 Benefits of tillage practices

The effect of tillage systems on crop yield is not uniform with all crop species, as various soils may react differently to the same tillage practice. Tillage effects on crop yield may also differ from one agro-ecological zone to the other. Nicou *et al.* (1985) experimented the effect of tillage on yields of various crops in the West African semi-arid tropics. The results showed that the yield of millet, sorghum, maize, rice, cotton and groundnut increased by 22%, 25%, 50%, 103%, 17%, 24% respectively. Zheng *et al*. (2014) found conservation tillage to significantly increase rice, wheat and maize yields by 4.1%, 2.9% and 7.5% respectively. Contour ridge or ridge tillage technology has been developed in Mali and has been beneficial in several West African countries such as Senegal and Gambia. Contour ridge increased maize yield by 38 %, sorghum by 39 % and cotton yields by 7 % in Mali; peanut and sorghum yields by 25 % in Senegal and maize yield in Gambia from 9 to 30 % (Doumbia *et al*., 2008). The semi-arid zone has the highest prospects for rapid tillage technological package development, firstly, because of the availability of animal draught power, secondly because of the crops and cropping systems used and, thirdly because of the rapid response of the zone to soil and water conservation and management practices to increase crop production (Ofori, 2013). The contour ridges significantly increased maize yield by 35 % and millet yield by 60 % in Mali (Jacques *et al.,* 2006). Hilger (2008) reported that after three years of experiment, maize yield increase for soil tillage treatments reached 2.0 to 2.7 Mg ha^{-1} without fertilizer and 3.9 to 4.2 Mg ha^{-1} with fertilizer application.

2.3 Liming

Liming is an important practice to achieve optimum yields of all crops grown on acid soils. According to Kaitibie *et al.* (2002), liming is the most widely used long-term method of soil acidity amelioration, and its success is well documented (Scott *et al.,* 2001). Application of lime at an appropriate rate brings several chemical and biological changes in the soils, which are beneficial in improving crop yields on acid soils (Fageria *et al.,* 2008). Liming raises soil pH, base saturation, and Ca and Mg and reduces aluminium concentration in acidic soils (Fageria *et al.,* 2004).

Plant growth improvement in acid soils is due to increasing pH that reduces toxicity of phytotoxic levels of Al (Fageria *et al*, 2008). Lorry (1999) stated that maximum availability of soil nutrients generally occurs in a pH range of 6.0 to 7.0. Maintaining a soil pH in this range also favours the presence of H_2P0_4 ions which are more readily absorbed by plants. Calcium released from applied lime in soil has been reported to enhance plant resistance to several plant pathogens (Fageria *et al.*, 2008), including *Erwinia phytophthora, R. solani, Sclerotium rolfsii, and Fusarium oxysporum* (Kiraly, 1976). Haynes (1984) reported that calcium forms rigid linkages with pectic chains and thus promotes the resistance of plant cell walls to enzymatic degradation by pathogens. Therefore, liming provides calcium, which can contribute to build up plant resistance to some pathogens.

Acidic soils are naturally deficient in total and plant available phosphorus. Phosphorus is a macronutrient that plays a number of important roles in plants. It is a key role in energy transfer and thus it is essential for photosynthesis and other chemio-physiological processes in plants. Adequate phosphorus results in higher grain production, improved crop quality, greater stalk strength, increased root growth and early crop maturity (Havlin, *et al.*, 2005). Deficiency in total and available phosphorus in acid soil is due to the fact that significant portions of applied P are immobilized due to precipitation of P as insoluble Fe/Al phosphates or chemisorption to Fe/ Al-oxide and clay minerals (Nurlaeny *et al*., 1996). Liming of acidic soils result in the release of P for plant uptake, an effect often referred to as ‘‘P spring effect’’ of lime (Bolan *et al*., 2003). Increase in availability of P in the pH range of 5.0 to 6.5 is associated with release of P ions from Al and Fe oxides, which are responsible for P fixation (Fageria, 1989). But at high pH (> 6.5) soluble P is precipitated as Ca phosphate (Naidu *et al.*, 1990)

Soil microbiological properties can serve as soil quality indicators. Soil acidity restricts the activities of beneficial microorganisms, except fungi, which grow well over a wide range of soil pH (Brady *et al*., 2002). Liming acidic soils enhance the activities of beneficial microbes in the rhizosphere and hence improve root growth by the fixation of atmospheric nitrogen because neutral pH allows more optimal conditions for free-living N fixation (Stephen, 2011). It can also suppress pathogens by producing phytohormones; enhance root surface area to facilitate uptake of less mobile nutrients such as P and micronutrients and mobilize and solubilise unavailable nutrients (Baligar *et al*., 1999).

According to McBride (1994), increasing soil pH through liming can significantly and adversely affect the adsorption of heavy metals in soils. Soil properties such as organic matter content, clay type, redox potential, and soil pH are considered the major factors that determine the bioavailability of heavy metals in soil (Treder *et al.*, 2005). Hence, liming certainly helps in reducing availability of heavy metals to crop plants.

Soil acidity is also responsible for low nutrient use efficiency by crop plants. Fageria *et al*. (2004) reported that liming acidic soils improved the use efficiency of P, and other micronutrients by upland rice genotypes. In this study, efficiency of these nutrients was higher under a pH of 6.4 than with pH 4.5. The liming improved efficiency of nutrients through soil acidity management by enhancing their availability, and robust root system (Fageria *et al.*, 2004).

2.4 Supply of phosphorus from Tilemsi Phosphate Rock (TPR)

Soil acidity and phosphorus deficiencies limit crop production in many tropical soils. Lime and inorganic phosphate fertilizers are used in developed countries to remedy these problems. However, due to increasing costs and unavailability when needed, their use among smallholder farmers in developing countries is not widespread. This, coupled with concerns for environmental protection and sustainability, has renewed interest in the use of alternative cheaper locally available materials. The use of phosphate rocks (PR) and organic materials has in particular received increased attention in recent years in Africa. In addition to provision of P, PRs have Ca and Mg which make them assume a significant role as a potential tool for sustaining soil productivity by reducing soil acidity through its liming effect. Although P in most organic matter is low, the latter can influence soil parameters such as soil pH, exchangeable Al, and Ca, which greatly influence crop growth (Bareeleng, 2011).

Mali is endowed with a phosphate rock containing about 27% P_2O_5 located in the Tilemsi Valley north of Gao. Tilemsi phosphate rock (TPR) is a medium reactive rock suitable for direct application. TPR has a solubility of 61% in formic acid. This reactivity is attributable to a relatively high degree of carbonate substitution for phosphate in the rock minerals (Henao, 1999).

The use of TPR as a P fertilizer has been suggested by many researchers. Review of earlier research conducted in Mali (Pieri, 1973; Poulain, 1976; Thibout *et al*., 1980) showed that TPR could be used for direct application on crops and the recommended rates ranging from 20-80 kg P_2O_5/ha (70-290 kg/ha of TPR). The TPR is to be applied on the fallow and incorporated by a late ploughing at the end of the rainy season. DNA, (1982) recommended 200 kg/ha^{-1} of TPR applied on the fallow and incorporated by ploughing later. Additional work conducted by the Semi-Arid Food Grain Research and Development (SAFGRAD) in farmers' fields recommended that TPR be used at a rate of 300 kg/ha. Compagnie Malienne pour le Développement du Textile (CMDT) has recommended for cotton, maize, sorghum, or groundnut rotation the application of 300 kg/ha of Tilemsi phosphate rock (TPR) on the fallow, incorporated by ploughing at the end of the rainy season. For rice, the Office du Niger (ON) recommends applications of 500 kg/ha of TPR.

Phosphorus fertilization alternatives in Mali, based on TPR, include direct application of TPR either basal or annual, application of TPR supplemented with low amounts of P soluble fertilizers, and application of TPR combined with organic manures. Generally, TPR is applied manually and incorporated into the soil prior to planting (Julio, 1999).

2.5 Soil Organic matter

Soil organic matter (SOM) is the most important indicator of soil quality and productivity and consists of a complex and varied mixture of organic substances. Organic matter increases soil porosity, thereby increasing infiltration and water-holding capacity of the soil, providing more water availability for plants and less potentially erosive runoff and agro-chemical contamination (Lal *et al*., 1998). The structure of the fine-textured soils may be improved by liming, as a result of increased soil organic matter content and enhanced flocculation of Ca-saturated clays.

Microbial activity and the cycling of nutrients through soil organic matter substantially impacts plant nutrient availability. The soil solution concentration of N, S, P and several micronutrients are intimately related to the organic fraction in soils (Havlin *et al.*, 2005). Erich *et al.* (2002) noted that carbon containing residual materials, such as compost, bio-solid, or manure, have the potential to increase soil organic matter levels to these and improve soil quality when added soils in significant quantities.

There is considerable evidence in the literature to suggest that the application of organic material to soil increases P solubility (Sanyal *et al*., 1991). Organic matter may be sorbed to soil particles at non-specific sorption sites, which would increase the surface negative charge of the particle. This would reduce the electrostatic attraction of P to the soil and keep more P in solution. In general, manure application increases both inorganic and organic soil P levels; many types of manure have a relatively high percentage of their total P in inorganic forms. The research conducted by Erich *et al.* (2002) revealed that both amended and no amended soils contained levels of plant-available P within the range considered optimum for crop production, 7.5-20 mg/P/kg

2.6 The combined use of organic and mineral fertilizers

The continued increase in prices of inorganic fertilizers and the local availability of organic manures necessitates promotion of use of both fertilizers so as to improve, not only soil properties, but also to increase crop yields and reduce the occurrence of weeds such as striga. It has been reported by Sanginga *et al*., (2009) that higher benefits are obtained by the overall improvement in soil physical, chemical and biological properties from recycling of organic materials in soil, and increase in the availability of plant nutrients. According to Sanginga *et al*., (2009), the use of inorganic fertilizers is indispensable in alleviating nutrient constraints and is central in integrated soil fertility management (ISFM) practices for improving crop production. The craft of ISFM involves making the best use of affordable fertilizers, available organic resources and accessible agro-minerals (Sanginga *et al.,* 2009).

Inorganic fertilizers have a high concentration of nutrients that are rapidly available for plant uptake and they can be formulated to supply the appropriate ratio of nutrients to meet plant growth requirements. Today, a wide range of inorganic fertilizers are required to maintain soil fertility and sustainable agricultural systems. Farmers are aware that without inorganic fertilizers the productivity of their crops and pastures will drop and soil nutrient levels will decline rapidly (Waswa *et al*., 2007).

Organic inputs contain nutrients that are released at a rate determined in part by their chemical characteristics or organic resource quality. However, organic inputs applied at realistic levels seldom release sufficient nutrients for optimum crop yield. Combining organic and mineral inputs has therefore, been advocated as a sound management principle for small-holder farming in the tropics because neither of the two inputs is usually available in sufficient quantities and because both inputs are needed in the long term to sustain soil fertility and crop production (Vaulauwe, 2010).

The beneficial effect of combined use of organic and inorganic fertilizers is well established. Organic manures not only increase nitrifying activities of micro-organisms but reduce N losses by increasing CEC of soil (Gasser, 1964). The addition of plant litter/leaves can improve the structure, permeability, and stability of soil (Walsh *et al.*, 1977). Green manuring maintains and improves soil structure by addition of organic matter and minimizes N, P, K fixation in all types of soils (Repetto, 1986). Kalebonye, (2011) reported that application of organic materials increase the ability of microorganisms to produce polysaccharides, which improve soil structure while humus enhances the utilization of fertilizer nutrients by plants and also decreases leaching losses by increasing water holding capacity of the soil. According to Mukuralinda (2007), the best practice is one that combines lime, organic manure and inorganic fertilizers. This has been observed to be the most appropriate technique of addressing the problem of soil acidity and enhancing soil fertility in Rwanda (Ruganzu, 2009). Significant yield increases have been observed in areas where the organic and inorganic nutrients sources have been applied together with lime (Nabahungu, 2003). In the Himalayas India, integrated use of chemical fertilizers and farm yard manure enhanced the grain yields significantly for maize and wheat in comparison to use of sole chemical fertilizers (Sharma *et al*., 2003). Negassa *et al.* (2001) also observed that the use of 5 tonnes compost ha^{-1} alone and integration with low rates of N, P fertilizers was economically best for maize production with a saving of 85 kg N ha^{-1}. Khalid *et al*. (2005) indicated that FYM + crop residues can substitute 50% NPK for wheat production and their residual effect was equivalent to 50 % of the recommended dose of NPK as chemical fertilizer on the yield of succeeding crop in rice-wheat cropping system.

2.7 Remote sensing and Geographic Information System

The need to integrate remote sensing and GIS into soil fertility management necessitated the review of the pertinent literature in this subject matter area as presented in the following sections.

2.7.1 Remote sensing

Remote sensing is defined as the science of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand *et al*., 2004).

Remote sensing uses satellite images since the launch of Landsat-1, the first Earth resource satellite in 1972; remote sensing has become an increasingly important tool for the inventory, monitoring, and management of earth resources. The increasing availability of information products generated from satellite imagery data has added greatly to our ability to understand the patterns and dynamics of the earth resource systems at all scales of inquiry (Bawahidi, 2005).

A particularly important application of remote sensing is the generation of information on the soil from satellite imagery. Over the past few decades, the Earth's surface has witnessed major changes in land use. These changes are likely to continue, driven by demographic pressure or by climate change. In this context, monitoring tools are needed for maintaining a sustainable ecological status, improving soil conservation and water resource management. Floods, excess runoff, soil erosion, and related contamination and disequilibrium of the water and carbon cycles are, among others, key issues that are controlled and influenced by soil surface characteristics. The implementation of sustainable agricultural, hydrological, and environmental management requires an improved understanding of the soil, at increasingly finer scales (Zribi, 2011). Compared to the more traditional mapping approaches such as terrestrial survey and basic aerial photo-interpretation, soil information mapping using satellite imagery has the advantages of low cost, large area coverage, repetitivity and computability (Franklin, 2001). Consequently, soil information products obtained from satellite imagery, such as soil degradation maps, data and GIS layers, have become an essential tool in many operational programs involving soil resource management.

One of the most important applications of remote sensing is the monitoring of processes occurring on the Earth including soil nutrient depletion. The use of satellite imagery data in soil fertility management and planning is an extremely promising one. As a result of the recent development of sensor technology, the quality of satellite imagery available for soil mapping is improving rapidly. Particularly noteworthy in this regard is the improved spatial and spectral resolution of the imagery captured by new satellite sensors. The use of imagery from high-resolution sensors on satellites such as IKONOS and QuickBird has proved that data from space-borne sensors can provide a viable alternative to aerial photography in many applications including detailed land cover mapping, water resources assessment, irrigation management and crop and yield mapping (Lillesand *et al*., 2004; Trietz *et al.*, 2004). It was predicted that in the near future, more than 50 percent of the current aerial photo market will be replaced by high-resolution satellite imagery (Fritz, 1996). At the same time, rapid advances in the computer science as well as other information technology (IT) fields have offered more powerful tools for satellite image processing and analysis. Image processing software and hardware are becoming more efficient and less expensive. Access to faster and more capable computer platforms has aided our ability to store and process larger and more detailed image and attributes data sets.

Digital image processing involves manipulation and interpretation of digital images with the aid of computer technology. Recently, digital image processing is central to efficient use of satellite imagery in soil management studies. A key task of satellite image processing is to develop image data analysis approaches appropriate to a particular resource management application (Treitz *et al*., 2004). The extraction and classification of soil types from satellite imagery is probably the most important objective of digital image analysis in geoscience. Conventional image classification techniques are based on the spectral response patterns of terrain features captured in satellite imagery (Bawahidi, 2005). While conventional spectral classifiers are widely used and have achieved a fairly large amount of success, the resulting classification maps are often very noisy.

2.7.2 Geographic Information System

A GIS is a computerized data management system which has the ability to capture, store manage retrieve analyse and display very large databases of spatially referenced information (Clarke, 1999). The Environment System Research Institute (ESRI, 2010) defined a GIS as a system of data, hardware, software and procedures designed to support the capture, management, manipulation, analysis, modelling and display of spatially referenced data for solving complex planning and management operations.

Densham (1991), reported, GIS functionalities, especially the manipulative and analytical capacities, enhance the problem-solving environment in two ways. First, the problem can be examined to increase the level of understanding and to refine the definition. Secondly, the generation and evaluation of alternative solution to the problem enables the identification of potential conflict and trade-off and the unanticipated impacts resulting from proposed solutions.

GIS is very important in soil fertility management. Landscape (topography, vegetation, soil, etc) and soil components and their variability can be mapped using GIS. The use of such maps as a decision support tool for soil nutrient management is very helpful for adopting a rational approach compared to farmer's practices or blanket use of state recommended fertilization. It also reduces the necessity for elaboration plot-by-plot soil testing activities. Furthermore, GIS provides a more integrated approach to problem-solving and an interdisciplinary understanding of the decision context (Kliskey, 1995)

2.7.3 Geographic Information System and remote sensing integration

The process of interpretation, whether visual or automatic, transforms data contained in the image to elements associated with a geographic location. Therefore to integrate the information collected by remote sensing to information spatially referenced is a very great advantage because this information can then be used in a process of resource management, in combination with data from other sources, such as economic or ecological data (Bonn *et al.*, 1993). However, the transfer of data from one to the other is not easy. It is done by the complex systems of transformations.

In terms of data creation and data collection, remote sensing provides data to the GIS to be processed. It is located upstream of GIS and creates geographic data. GIS then completes remote sensing data. Geographic information allows the georeferencing of the processed image, and the integration of the result of digital processing of image with the results of geographic information processing. This integration also allows updating pre-existing maps by using recent data from satellites. This update is also possible through the use of Global Positioning System (GPS), which uses the potential of positioning satellites to identify points on the surface of the globe. These positions will generate points, arcs or polygons in an information system. Remote sensing and GIS are seen as sources of information on the natural environment and offer enormous potential for the analysis and management of natural resources particularly, soil resources. GIS, in effect, allows the acquisition of databases that are real tools for decision support. These databases can be update regularly for various and accurate studies.

2.7.4 Use of remote sensing in assessing soil degradation and some soil properties

Characterization of soil properties is one of the earliest applications of remotely sensed data in soil degradation issue. A majority of the studies examining quantitative relationships between remotely sensed data and soil properties have focused on the reflective region of the spectrum (0.3 to 2.8 µm), with some relationships established from data in the thermal and microwave regions. Most of the spectral responses in the reflective spectrum can be related to differences in organic matter content, iron content, and texture (Stoner *et al.*, 1981). The soil property that is most directly correlated to reflectance-based data is soil albedo (Post *et al.*, 2000). Soil albedo is the reflectance capacity of the soil, in other word, the ability of the soil to send enough information to the satellite. Therefore, multispectral images have shown potential for the automated classification of soil mapping units (Leone *et al.,* 1995). Such direct applications of remote sensing for soil mapping are limited because several other variables can impact soil reflectance such as vegetation, moisture content, temperature, tillage practices etc. However, bare soil reflectance could have an indirect application in interpolating the results of gridded soil samples (Barnes *et al.*, 1996).

In the case of soil degradation, in addition to the difference in organic matter content and iron content, the change in soil quality can be studied through vegetation. The subtle changes in colour and the variations in the structure and the spatial distribution of the vegetation can be an indicator of soil quality. Vegetation spectral response has been used to infer soil conditions (Mougenot, 1993). Wiegand *et al*. (1994) and Mougenot (1993) found that vegetation index was useful in mapping soil salinity. The nitrogen status of crops has also been estimated using remotely sensed data (Blackmer *et al*., 1995; and Filella *et al*., 1995). Yang *et al*. (1996) described methods to utilize multispectral images of vegetated fields for the determination of within-field management zones for application to site-specific farming.

There are various methodologies for studying the changes in vegetation through satellite. One of these methodologies is the indices relating to the quantity of greenness (Chuvieco, 1998). The NDVI (Normalized Difference Vegetation Index) is a measurement of the balance between energy received and energy emitted by objects on Earth. When applied to plant communities, this index establishes a value for how green the area is, that is the quantity of vegetation present in a given area and its state of health or vigour of growth. The NDVI is a dimensionless index, so its values range from -1 to +1. In a practical sense, the values that are below 0.1

correspond to bodies of water and bare ground, while higher values are indicators of high photosynthetic activity linked to scrub land, temperate forest, rain forest and agricultural activity.

In proximal sensing, soil texture is typically determined by multiple linear regression or partial least-square regression. Calibration of these models is mostly done using data from a sample. Results show that these methods are useful tools for predicting soil texture, but calibration of the models is based on local conditions and therefore these models will typically not work outside the studied areas (Dematte *et al*., 2007; Minasny *et al.*, 2008; Thomasson *et al.*, 2001).

Apan *et al.* (2002) used ASTER bands 2, 8 and the first principal component of ASTER imagery for determining, broad texture classes. Differences between clay-rich and quartz-rich soil can be locally or regionally mapped based on specific absorption features. Clay minerals have typical hydroxyl absorption at 2200nm, referred to as the SWIR clay index (Chabrillat *et al*., 2002). This feature can be captured with bands 5 and 6 of ASTER. The Presence of quartz can be detected using thermal bands between 8000nm and 9500nm in which the reststrahlen feature occurs, which correspond with bands 10 to 14 of ASTER. The combination of ASTER bands 5 and 6 and thermal infrared bands 10 and 14 can then be used to discriminate both dark clayey soils and bright sandy soils from nonphotosynthetic vegetation on a local scale, but results are influenced by organic matter (Breeunig *et al*., 2008).

AVHRR (Advanced Very High Resolution Radiometer) has been used to map the spatial extent of clay content by means of multivariate prediction models (Odeh *et al.*, 2000). Landsat TM, SPOT and airborne spectroscopy have been used to determine different soil texture classes by correlation of image data with laboratory analysis (Barnes *et al.*, 2000). The different soils were classified with accuracy from 50% up to 100%. This study was conducted on a plot scale with an exhaustive soil sample dataset; due to the availability of this large dataset higher accuracies were obtained compared to other studies. Only few researchers explored Hyperion data for mapping soil texture; the main reason for this is the earlier mentioned low signal-to-noise ratio and additionally required heavy pre-processing. Even so, Chabrillat *et al*. (2002) successfully identified, after noise reduction, expansive clays in the Colorado Front Range Urban Corridor when vegetation cover was less than 10%.

In contrast with the use of optical imagery, there is little experience in using radar to retrieve soil texture. Singh *et al.* (2007) developed a modelling approach based on a Genetic Algorithm, which included empirical modelling to simultaneously retrieve soil moisture, roughness and texture from the dielectric constant derived from ERS-2 SAR backscatter data. Although the results were in agreement with field observations, they concluded that there are problems with the retrieval of input variables of the model.

Accurate and timely information about soil organic matter is essential for agricultural production and environmental research. During the past three decades, high altitude remote sensing coupled with laboratory based reflectance spectroscopy has emerged as an important technology for monitoring the Earth's agricultural resources. The soil spectral responses due to soil colour have long been associated with native soil fertility and are also useful in determining the soil organic matter:

- The soils of higher organic matter content are generally darker in colour and are less reflective than those soils with lower organic matter content.

Soils with thick, dark surface horizons are often separated from other soils in many soil classification systems, which emphasize the importance of these soils both as a medium for plant growth and also as an indicator of land value for agricultural and urban area.

- Bare soil areas with high-residue content from the previous crop may mask soil spectral responses. The use of high spatial digital terrain models (DEM) produced by remote microwave or laser techniques can provide a better understanding of soil formation and surface moisture movement and hence aid in interpreting surface soil organic matter content (Gopal, 2015).

In general, nitrogen deficiency causes a decrease in leaf chlorophyll concentrations, leading to an increase in leaf reflectance in the visible spectral region (400-700 ηm). However, several other stresses (pest and diseases) may also result in increased plant reflectance due to reduced amount of chlorophyll (Carter *et al*., 2001). Osborne *et al*. (2002) showed the utility of hyper spectral data in distinguishing nitrogen and phosphorus at the leaf and canopy level, but the relationships were not consistent over all plant growth stages. Spectral reflectance peaks resulted from derivative analysis of spectral reflectance found to be good technique for stress detection. The position of the inflection point in the red edge region (680 to 780 ηm) of the spectral signature, termed as red edge position (REP), is affected by biochemical and biophysical parameters. Shifts in the REP to longer or shorter wavelengths have been used as a mean to estimate changes in foliar chlorophyll or nitrogen content and also as an indicator of vegetation stress. Cho *et al.* (2006) have used linear extrapolation method for extracting REP that has shown high correlations with a wide range of foliar nitrogen concentrations for both narrow and wide band width spectra.

Diagnosing a specific nutrient deficiency with remote sensing data can be difficult when plants are subjected to deficiencies of multiple elements.

Soil iron can be seen as an indicator of soil fertility and the age of the sediments (Bartholomeus *et al.,* 2007). Over the years, proximal sensing has proven to be useful for determining soil iron content in soil samples and at plot scale (Demattê, 2002). But also, remote sensing imagery has been successfully used for determining the presence of iron over areas up to 500 km^2. Both soil colour (Escadafal, 1993) and absorption features have been used to derive iron content (Warell, 2003). Iron oxide and iron hydroxides have specific absorption features that are located in the VNIR and can be measured from multispectral or imaging spectrometer images (Abrams *et al.*, 1995). However, these features are confounded if there is vegetation cover (Xu *et al.*, 2004). Only a few methods have been developed to quantify soil iron content. Though Landsat TM has been used for this purpose, the low spectral resolution means that the absorption features are not unequivocally discernable and therefore the results are not accurate (Deller, 2006). Bartholomeus *et al*. (2007) were among the first to quantify soil iron content on the basis of airborne optical data. They determined the iron content in Mediterranean soils in partly vegetated areas, using ground-based spectral reflectance and airborne imaging spectroscopy. The use of two iron-related absorption features as well as a ratio-based Redness Index, which is the ratio of the reflectance in the red part of the spectrum divided by the sum of total visible reflectance, gave fairly good correlations (R^2=0.67 and R^2=0.51, respectively) on samples measured under laboratory conditions. Unfortunately, the relations were weak (R^2=0.26) when applied to airborne ROSIS (Reflective Optics System Imaging Spectrometer) data. The relations appeared to be sensitive to vegetation cover, but a combination of the Redness Index and relations based on the absorption feature made the model more robust against the influence of vegetation cover (Bartholomeus *et al*., 2007).

2.7.5 Use of interpolation in assessing some soil properties

According to Querido (2008), almost all natural processes, soils in particular, develop over a large area or region and their spatial extent depends on climate, parent material, organisms, time, and topography. Data collected in one region show that neighbouring samples tend to have similar values and the similarity decreases with increased distance between samples. This spatial correlation is used to investigate whether point values are randomly distributed or whether the values have a relation to each other with distance. The spatial autocorrelation structure can be modeled by the variogram (Goovaerts, 1997).

According to Kravchenko *et al*. (1999), precision agriculture applies principles of farming according to the field variability, which creates new requirements for estimating and mapping spatial variability of soil properties. Improvement in estimation quality depends, first, on reliable interpolation methods for obtaining soil property values at unsampled locations and, second, on appropriate application of the methods with respect to data characteristics.

The interpolation techniques commonly used in agriculture include inverse distance weighting and kriging. Both methods estimate values at unsampled locations based on the measurements from the surrounding locations with certain weights assigned to each of the measurements. Inverse distance weighting is easier to implement, while kriging is more time-consuming and cumbersome; however, kriging provides a more accurate description of the data spatial structure, and produces valuable information about estimation error distributions (Kravchenko *et al*., 1999).

2.7.6 Mapping of some soil properties

Soil surveyors consider the topographic variation as a base for depicting soil variability. Even with the aerial photographs only physiographic variation in terms of slope and aspects and land cover are being practised for delineating the soil boundary. Multispectral satellite data are being used for mapping soil up to family association level (1:50,000). The methodology in most of the cases involves visual interpretation (M-C. Girard, 1995). However, interpolation technique especially kriging is also used in mapping soil spatial variability.

Visual interpretation is based on shape, size, tone, shadow, texture, pattern, site and association. This has the advantage of being relatively simple and inexpensive. Soil mapping needs identification of a number of elements. The elements which are of major importance for soil survey are land type, vegetation, land use, slope and relief. Soils are surveyed and mapped, following a 3 tier approach, comprising interpretation of remote sensing imagery and/or aerial photograph (Mulder, 1987), field survey (including laboratory analysis of soil samples) and cartography (Sehgal *et al*. 1989). Several workers (Karale, 1992; Kudrat et al., 1993; Kudrat et al., 1990; and Sehgal, 1995) concluded that the technology of remote sensing provides better efficiency than the conventional soil survey methods at a reconnaissance (1:50,000) and detailed (1:10,000) scale of mapping.

Kriging is a geostatistical interpolation technique which considers both the distance and the degree of variation between known data points when estimating value in unknown areas. It is a weighted linear combination of the known sample values around the point to be estimated (Isaaks *et al.,* 1989). According to ESRI (2010), Kriging assumes that at least some of the spatial variation observed in natural phenomena can be modelled by random processes with spatial autocorrelation, and require that the spatial autocorrelation be explicitly modelled. Kriging techniques can be used to describe and model spatial patterns, predict values at unmeasured locations, and assess the uncertainty associated with a predicted value at the unmeasured locations ESRI (2010). These can be achieved by using a semivariogram which kriging provides. The semivariogram mathematically describes the way the variance of a property changes as the distance and the direction separating any two points vary (Oliver and Webster, 1991).

The spatial correlation is usually represented by the variogram or covariance models (Goovaerts, 1997; Webster *et al*., 2001; Lark, 2002b). Variograms and covariance functions are the fundamental tools for modeling dependent data observed over time, space, or space-time (Chunsheng, 2005).

The interpretation of the variogram is a key factor in kriging. The variance usually increases as the lag distance increases corresponding with more or less strong correlation or spatial dependence at the shortest distance. Thus, places which are closer to each other are expected to have similar soil characteristics than those further apart which may differ. A prerequisite in the interpretation of variograms is good understanding of its associated terms. This is illustrated in the following figures

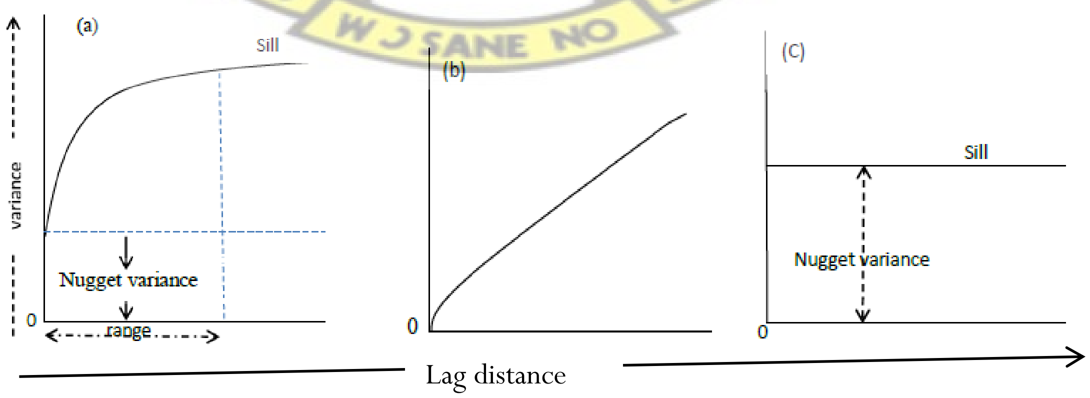

Figure 2.1: Three forms of variogram function: (a) bounded, (b) Unbounded, (c) Pure Nugget (Oliver and Webster, 1991)

In Figure (a), the variogram increases till the sill variance is reached, i.e where the variance is constant. Such a variogram is referred to as a bounded variogram, and the distance at which the sill is reached is referred to as the range which marks the limit of the spatial dependence.

The nugget variance, on the other hand, is the distance from the x-axis to the point where the variogram has a positive intercept on the y-axis and corresponds to the wholly random variation. This is also indicative of the variation within shorter distances than the sampling interval.

Figure (b) is an unbounded variogram in which the variogram increases indefinitely whilst.

Figure (c) presents a situation where the variogram is completely flat. This indicates that there is no spatial dependence in the data (Oliver and Webster, 1991)

2.8 Available soil information in Mali

The search for information in Mali for use in this study revealed the following, FAO soil map at the scale (1974) 1:5, 000, 000, Terrestrial Resources Inventory map of Mali (1983). Unfortunately, these studies are in small scale and not suitable for the requisite large scale soil information needed in this study. Consequently data were carried from internet database and field measurement.

2.9 Knowledge gaps

Agriculture soil fertility and water management is a challenge for smallholder farmers in Mali. The use of adapted soil management practices combined with local available organic amendment is supposed to be the main solution against soil fertility decline and low crop productivity. Also, combine soil fertility management practices with good and reliable spatial information on soils, become more important because it helps to diagnose the magnitude of the problem and helps for appropriate decision making.

Remote sensing and GIS have been identified as good tools to achieve these objectives but they are rarely used in soil issue in Mali. The only use of Remote Sensing in soil fertility issue in Mali was done by the Carbon Communities Project in 2005. The objective was to assess the potential for increasing soil carbon level in Mali. Satellite images were used to follow the fields under different tillage practices. The study revealed the benefit of the use of remote sensing and ridge tillage to assess and improve soil carbon level. However the study was limited to one field and concerned only soil carbon.

The current study was initiated to appreciate the efficiency of the use of remote sensing and GIS in soil fertility management at village scale and to assess the effect of Profeba under ridge tillage and hoe tillage on acid soil. The use of Profeba compost under adapted tillage practice is a promising technology which could be used by farmers to increase soil pH, soil fertility and improve crop yields on poor acid soil. Profeba, an improved organic material is not well used by smallholder farmers in Mali. Little is known about its effect on acid soil.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study site

The research was carried out at Siguidolo (Figure 1), located in the Sahelian zone of Mali between 6^{O} 44’ 54” and 6 ^{O} 46’ 12” W and 12 ^{O} 54’ 00” and 12 ^{O} 56’ 24” N. Siguidolo is about 3 km from Konobougou and 150 km from Bamako.

Rainfall is unimodal and ranges from 600-800mm. Siguidolo is characterised by lateritic highlands alternating with moderate slopes and plains. The landscape of the region is characterized by flat surfaces with an average altitude of about 300 meters and hills that seldom exceed 400 meters in altitude (Kablan, 2008). Soils in the area have been classified as Ultisol (USDA, 1999) from Precambrian Sandstone materials (Dabin et *al*., 1979). According to Traore (2003), those situated on the top or middle of the toposequence may contain gravel. Those at the bottom of toposequence are prone to waterlogging in the rainy season.

The vegetation is classified as savanna bushlands (Kablan, 2008). The sparse Shea butter trees (*Vitellaria paradoxa, Gaertn*) and Baobab (*Adansonia digitata, L*.) and Nere (*Parkia biglobosa*) were found on the bottom of toposequence; shrubby vegetation with *Guiera senegalensis, Combretum gasalense* and *Combretum micranthum* and grassy vegetation with *Pennisetum pedicelatum* and *Pennisetum purpureum* were on the top to middle of the toposequence (Traore, 2003). Figure 3.1 shows the geographic location of Siguidolo in Mali.

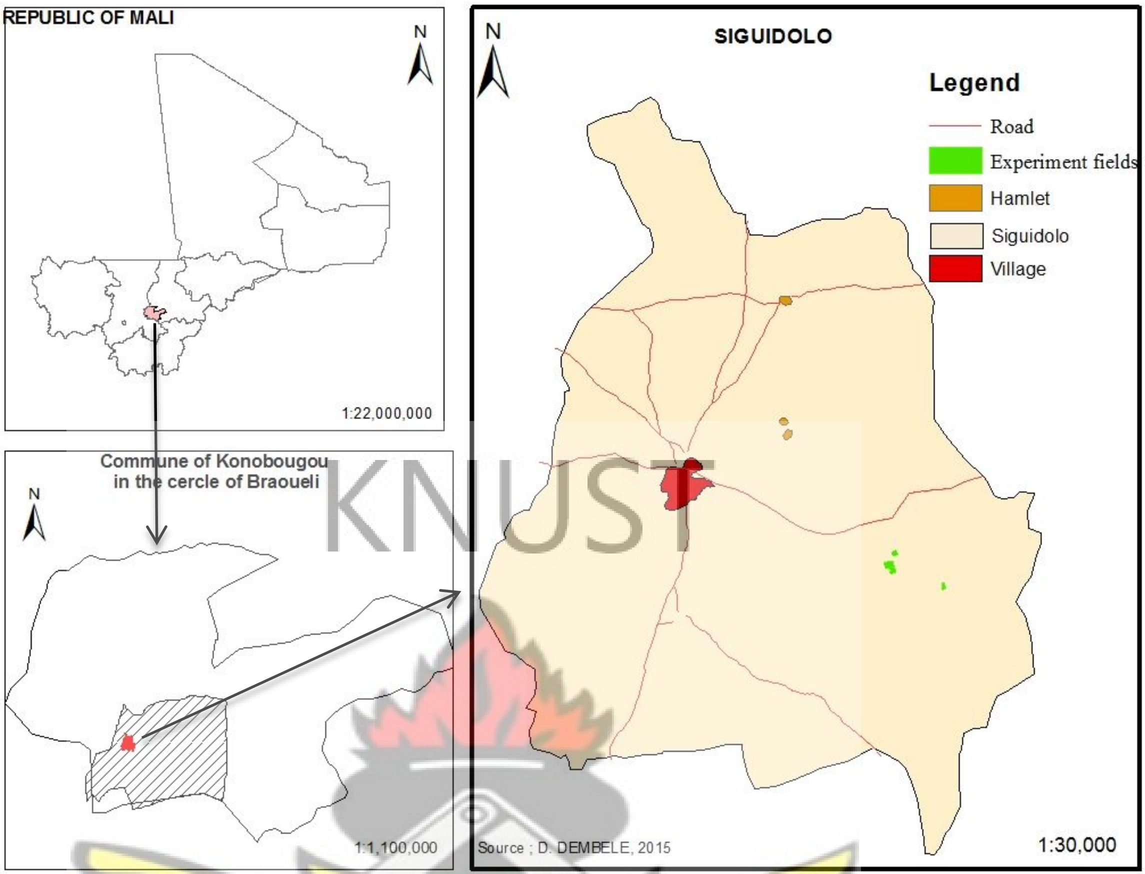

Figure 3.1: Geographic location of Siguidolo

3.2 Data collection

A major objective of this study was to develop research methodology that would combine satellite image, GIS, laboratory analysis and survey data to provide information on the spatial distribution of soils, their physical and chemical characteristics, vegetation and cropping systems at Siguidolo. The aim was to improve decision-making for appropriate soil fertility management. The first task was to identify the potential sources of data and evaluate their suitability for use in this study. The second task was to identify gaps in the database and the extent to which they could be completed by field survey data.

Images from Landsat 8 Operational Land Imager (Path 198, Row 52) with a spatial resolution of 30 m and recorded in March 2013 and DEM from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) with spatial resolution of 30 m were downloaded form United States Geological Survey (USGS) database.

Quick bird taken March 2005 image having a spatial resolution of 4 m and covering 75% of the study site was accessed from the Institute of Rural Economy (IER), Mali.

Onsite measurements and survey data were collected to fill the gaps in the data obtained from the various sources. The survey data were also used for ground truthing of soil map and the NDVI land cover mapping derived from the satellite images. The data collected are presented in Table 3.1 GPS was used in carrying out the surveys which comprised 52 sampling points for soil characteristics, agronomic practices, fertilizer use, land use and crop yields; and 36 out of 38 households cultivating 182 fields.

Table 3.1: Data type and their sources

Data type	**Source**
Satellite imagery	USGS database, IER
DEM	USGS database
Topographic sheet	Geographic Institute of Mali
Boundary of the study site	Survey
Farmers' fields	Survey
Fertilizers	Survey
Crop yields	Survey
Land use	Survey
Soil texture	Laboratory analysis
Soil pH	Laboratory analysis
Organic carbon	Laboratory analysis
Nitrogen	Laboratory analysis
Phosphorus	Laboratory analysis
Potassium	Laboratory analysis

3.3 Data processing for the delineation and mapping of soil units and vegetation

The methodology for achieving specific objective I comprised the use of remote sensing and GIS tools in processing the satellite images with the view to delineating and mapping the soil units and vegetation of the study area with a complement of ground truthing

3.3.1 Delineation and mapping of soil units

ERDAS imagine, a remote sensing tool, was first used to pre-process the satellite images. Image enhancement, geometric correction and radiometric correction were made to improve the quality of the images. Image composite from band 3, 2 and 1 provided the best combination because they clearly differentiated changes in soil colour, soil cover, erosion marks and land use. Several filters were also tested and the neighbourhood (3x3) gave clear and smooth results. Filtering brought together the pixels of the same value and improved image interpretation.

The results obtained from ERDAS were integrated into an ArcGIS environment for visual interpretation. The aim of the visual interpretation was to stratify or identify soil units on the Landsat image. During this exercise, the soil units identified were digitized. A particular consideration was given to areas where the soil was easily recognizable (reference zone) than those where the interpretation of soil by proxy was apparently more difficult. All the contrasts (colour) on the image were taken into account. Twenty-four units were digitized, coded and mapped.

3.3.2 Delineation and mapping of vegetation

Landsat and Quick bird images were tested for NDVI (Normalized Difference Vegetation Index) calculation. NDVI is a dimensionless index that is indicative of vegetation density and is calculated by comparing the visible and near-infrared sunlight reflected by the plant surface (reflectance). The Quick bird image gave the best results because it has a good relationship with ground truthing. The vegetation Index was used to quantify the density of green leaf vegetation by the formula:

$$\text{NDVI} = \frac{(NIR - R)}{(NIR + R)}$$

Where

NI= Near Infra;

R= Red band

When NDVI calculation is applied on an image or a pixel, the output gives a value ranging between minus one (-1) to plus one (+1). A zero value means no green vegetation and close to +1 (0.8 - 0.9) indicates the highest potential density of green leaves. The spatial distribution of vegetation has significant implications on the soils of the area.

3.3.3. On-site measurements for ground truthing

Image interpretation and mapping of soil units and vegetation were completed by on-site measurement. During this step, known and unknown features marked on the image were verified on the ground and necessary corrections made. This involved visits to various parts of the study site. The 57 points, identified on the images, were accessed for data gathering on the kind of land use, crop, tillage practice, soil texture, the location on the topography, soil cover, and the presence of erosion marks.

3.4. Soil sampling for physical and chemical analysis and mapping

Specific objective 2 required field soil sampling for selected physical and chemical analyses and mapping. The locations of the sampling points were georeferenced using GPS to facilitate mapping of the various parameters of interest in a GIS domain.

3.4.1 Soil sampling

Stratified sampling using the soil units map was carried out to provide a comprehensive spatial database on soil physical and chemical properties. Fifty two locations were sampled and georeferenced. A composite of soil samples bulked from three points spaced about 20 m apart were taken from a 0-20 cm depth and saved in plastic bags for laboratory analysis of pH, N P K and C. The location of the sampled points is presented in Figure 3.2

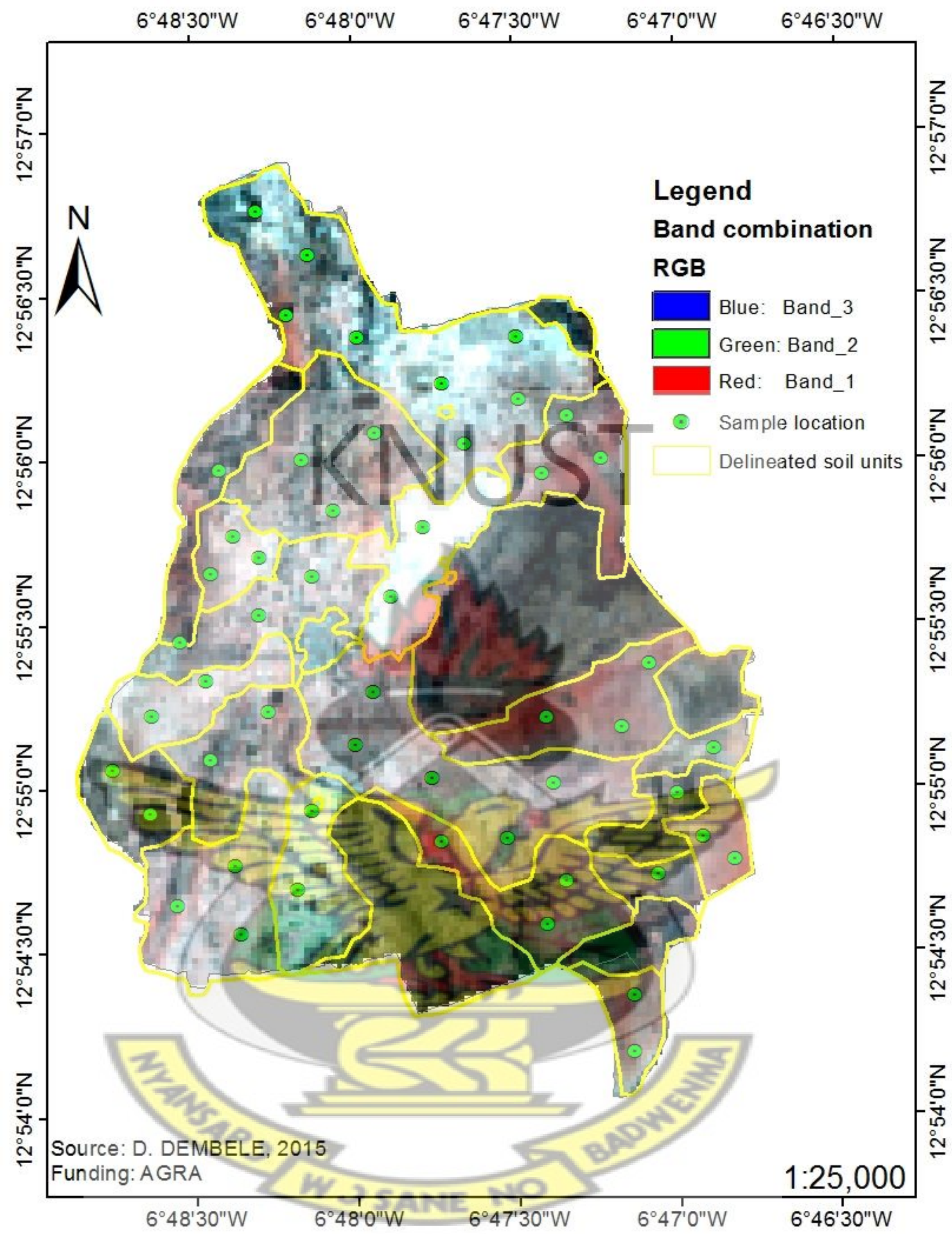

Figure 3.2: Location of soil sampling point at Siguidolo

3.4.2. Laboratory analysis of soil samples

The detailed description of the method of analyses is presented in section 3.10 with the following as the summary. Laboratory analysis of the soil samples was done to determine percentage clay, sand and silt using hydrometer method (Anderson and Ingram, 1993); soil pH by Anderson and Ingram (1993); soil organic carbon by the modified Walkley-Black wet oxidation method as outlined by Nelson and Sommers (1982) total nitrogen was determined by the modified Kjeldahl digestion method (Bremner and Mulvaney, 1982); available phosphorus by Bray P1- method (Bray and Kurtz, 1945); and exchangeable potassium by the method of Sparks et *al*. (1996).

3.4.3. Mapping of soil physical properties

Laboratory analysis results of clay, silt and sand were used to generate their respective maps using Arc-GIS and its thematic analysis function combined with the results of visual interpretation and interpolation. The soil textural triangle was used to determine soil texture for mapping purposes. Figure 3.3 shows the process of producing soil physical properties' maps.

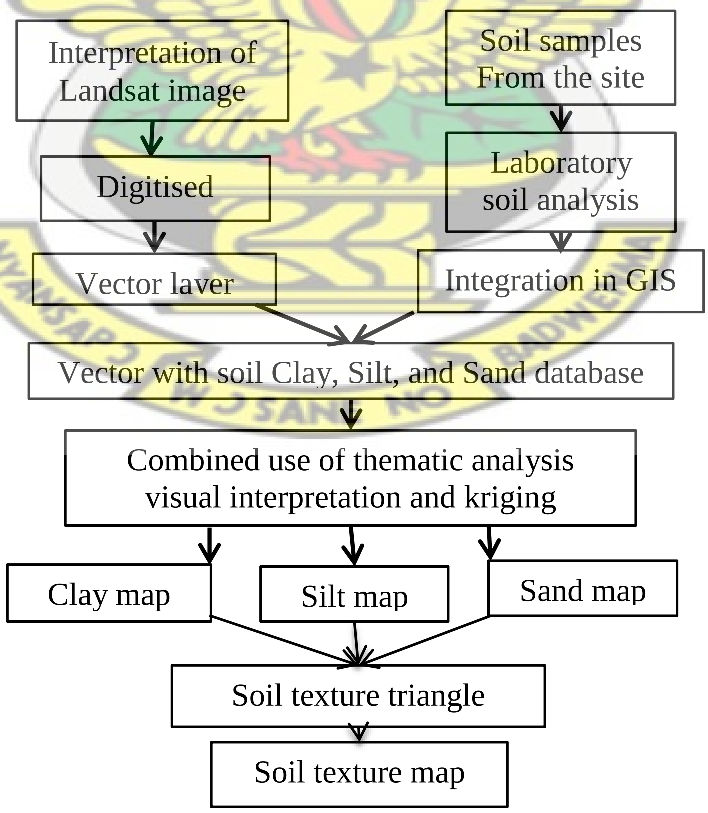

Figure 3.3: Flow-chart for mapping soil physical properties.

3.4.4. Soil nutrients and fertility mapping

The laboratory analysis of soil samples taken from the 52 georeferenced points provided quantitative data on pH, SOC, N, P, K which were used in an ArcGIS domain to produce their respective maps. An overlay of the SOC, N, P and K maps in the ArcGIS environment allowed the generation of a soil fertility status map of the study site. The flow chart for the production of the maps is presented in Figure 3.5

3.4.5. Spatial structure and variability of soil chemical properties

Various methods were used to generate information on the spatial structure and variability in measured soil chemical properties (pH, SOC, N, P and K). These comprised: Genstat statistical package, semivariograms and kriging.

Genstat package was used to summarize the measured data and to describe the degree of spatial variability

Normality test was used to test if a sample of data came from a population with a specific distribution.

Semivariogram was used to characterize the degree of dependency among the measured data

Kriging was used to extrapolate information from the sampled point to the unsampled location and provide the spatial structure of the selected soil nutrients. The flow-chart for the spatial structure analysis is presented in Figure 3.4

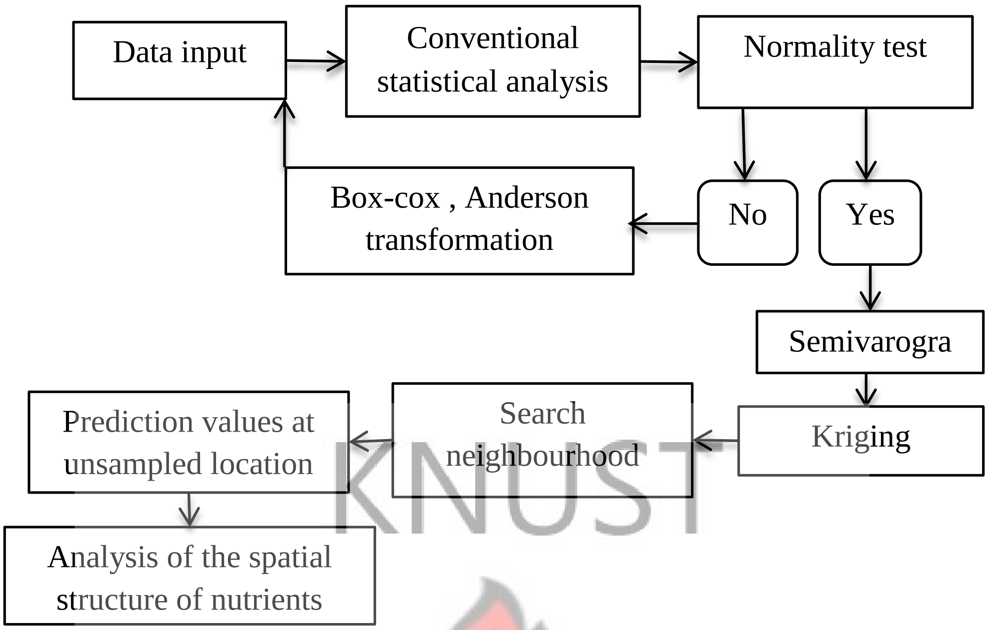

Figure 3.4: Flow chart for spatial structure analysis

An overlay of the three classes of N P K and C in the ArcGIS environment allowed generating soil fertility status map. Figure 3.5 shows the process used to produce the soil fertility map.

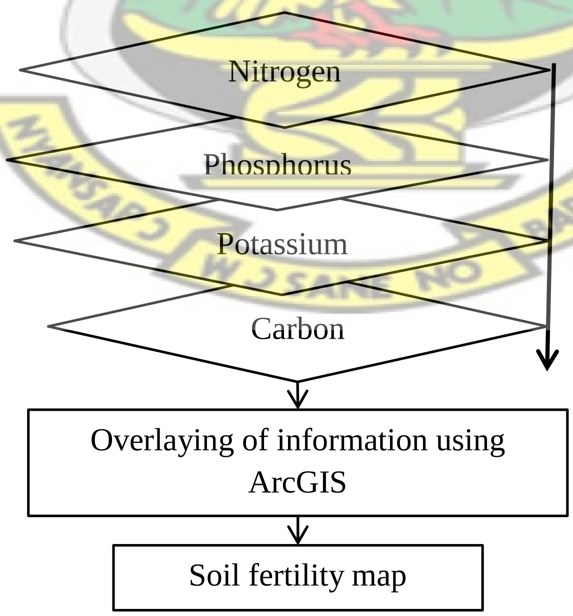

Figure 3.5**:** Flow-chart for generating soil fertility status map

3.4.6 Decision making for experimental field and soil amendment

Based on analysis and interpretation of soil physical and chemical characteristics and agronomic practices, a representative area of the study site was chosen for detailed experimentation on the impact of sole profeba compost and its combination with Tilemsi Phosphate Rock and agricultural lime and different tillage practices on crop productivity. This was to facilitate the identification of the best combination of soil amendments and tillage practices to correct soil acidity and improve soil fertility and crop productivity in the study site. Emphasis was laid on the most predominant soil type based on soil texture to facilitate the extrapolation of the results over a larger area. The experimental details are described in the next section. Figure 3.6 shows the flow- chart of decision making in the selection of experimental site. The experimental details are presented in the following sections.

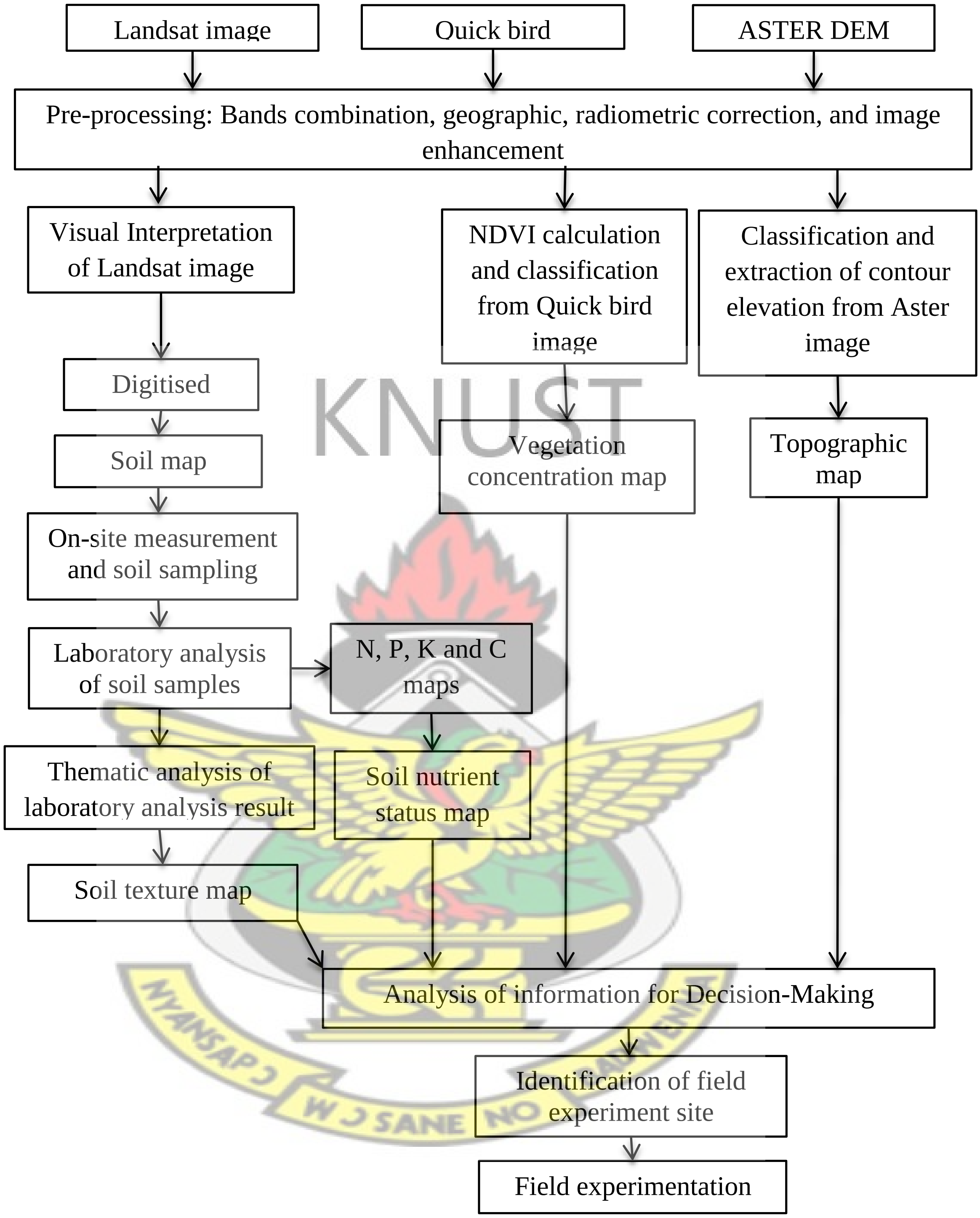

Figure 3.6 Decision making flow-chart for the selection of experimental field.

3.5. Field experimentation on the impact of tillage and soil amendments on selected soil physical and chemical properties

This experiment was carried out to address specific objective three of this study. The components are presented in the following sub-sections

3.5.1 Selection of experimental site

A one year bare fallow field with a sandy loam acidic soil was selected for the experiments.

3.5.2 Experimental Design

Two experiments were piloted with millet (*Pennisetum glaucum*), and sorghum (*Sorghum bicolor L. Moench*). Each test was a factorial experiment comprising two tillage practices (Ridge tillage and hoe tillage) and five forms of soil amendments P_0 = No amendment; P_1 = Profeba; P_2 = Profeba + Urea; P_3 = Profeba + Urea + TRP [Tilemsi Phosphate Rock] and P_4 = Profeba+ Urea + Lime in a randomized complete block design with three replications. Tillage practices were the main plots and soil amendments were the subplots. The dimensions of the subplots were 4 x 5m with 1m wide access between the main plots. Table 3.2 shows the amount of soil amendment applied.

Table 3.2: Soil amendments applied on millet and sorghum field.

Soil amendment	**Profeba** Mg ha^{-1}	**Urea** kg ha^{-1}	**TRP** kg ha^{-1}	**Lime** kg ha^{-1}
Control (No amendment)	0			
Profeba	5			
Profeba + Urea	5	50		
Profeba + Urea +RP	5	50	100	
Porfeba + Urea+ Lime	5	50		750

N.B. The amount of urea applied to sorghum was 100 kg ha^{-1}; Mg = Mega grams

3.5.3. Land preparation

Animal drawn mould board plough and tine harrows were used to prepare the ridged plots for seeding; the other plots were subjected to hoe tillage. The millet variety planted was Toronio and that of sorghum was CSM63E, locally called Jakumbe. They are improved varieties. The spacing of both millet and sorghum was 50 x 70 cm.

3.5.4. Crop management

Weed control was done by hoeing at 15 days and 30 days after planting. Animal drawn mould board ploughs and tine harrows were used for earthing up after 40 days. Grain yield was measured from the central three rows. Samples of yield components (stem, grain, and leaves) were collected.

3.5.5. Application of soil amendments

The main soil amendment used was Profeba. Profeba is an improved compost produced by the Industry of Production of Bacterial Fertilizers. Tilemsi Phosphate Rock (TPR) was from the commercial society of Seydou Nantoume. Profeba, TPR, and lime were mixed, weighed for each plot, spread and incorporated into the soil before planting. Urea as a source of nitrogen was applied 15 days and 30 days after planting.

3.5.6 Soil sampling and laboratory analysis

A composite of soil samples was collected before planting and after harvest for soil chemical and physical analysis. Each composite sample was a bulk of samples from 3 points at a depth of 0-20 cm stored in polythene bags for chemical and physical analyses. Profeba compost was also analysed at the soil water and plant laboratory of Institute of Rural Economy of Mali. The following parameters were analysed:

- **Soil texture determination**:

Particle size analysis was done by the hydrometer method (Anderson and Ingram, 1993). Fifty grammes of air dried soil were weighed into a conical flask and a dissolving agent sodium hexamegaphosphate added. After shaking on a reciprocal shaker at 400 r.p.m for 18 hours, the samples were transferred to sedimentation cylinders and topped up with distilled water to make up to the 1000 mL mark. A hydrometer was used to measure the density of the suspension of soil and water at 40 seconds and 3 hours and a thermometer used to measure the temperature at each reading. Percent Sand, clay and silt were calculated as:

$$\% Sand = 100 - \{H_1 - 0.2 \text{ x } (T_1 - 20) - 2.0\} \text{ x } 2$$

$$\% Clay = \{H_2 + 0.2 \text{ x } (T_2 - 20) - 2.0\} \text{ x } 2$$

$$\% Silt = 100 - (\% \text{ Sand} + \% \text{ Clay})$$

Where

H_1= first hydrometer reading,

H_2=second hydrometer reading,

T_1= temperature of suspension at first hydrometer reading,

T_2= temperature of suspension at second hydrometer reading

- **Soil pH***:*

Soil pH was determined by the McLean (1982) method. A 10 g of the soil sample in a 50 mL beaker was mixed with 10 mL of distilled water, stirred for five minutes and allowed to stand for 30 minutes. A pH meter (Eutech Instruments pH 510) zeroed by putting its glass electrode into distilled water was used to take the pH of the suspended solution at a temperature of 26.9 ^{o} C.

- **Soil organic carbon**

Soil organic C was determined by the modified Walkley-Black wet oxidation method as outlined by Nelson and Sommers (1982). Two grams (2.00 g) of soil was weighed into 500 mL conical flask and 10 mL of 0.166 M (1.0 N) $K_2Cr_2O_7$ solution added, followed by 20 mL concentration H_2SO_4 and allowed to cool on an asbestos sheet for 30 minutes. Two hundred millilitres of distilled water was added followed by 10 mL of H_3PO_4 and then 1.0 mL of diphenylamine indicator solution. This mixture was then titrated with 1.0 M ferrous sulphate solution until the colour changed from a blue-black colouration to a permanent greenish colour. A blank determination was carried out in a similar fashion in every batch of samples analysed without soil.

Calculation

$$\%C = \frac{\mathrm{N\ x\ (V_{bi} - Vs)\ x\ 0.003\ x\ 1.33\ x\ 100}}{\mathrm{g}}$$

Where;

N =Normality of $FeSO_4$ solution;

V_{bl} = mL of $FeSO_4$ used for blank titration;

V_s = mL of $FeSO_4$ used for sample titration;

g = mass of soil taken in grams;

0.003= milli-equivalent weight of C in grams (12/4000);

1.33 = correction factor used to convert the Wet combustion C value to the true C value since the Wet combustion method is about 75 % efficient in estimating C value , (i.e. 100/75 = 1.33).

- **Total Nitrogen**

Total nitrogen was determined by the modified Kjeldahl digestion method (Bremner and Mulvaney, 1982). A 10 g soil was weighed into a 250 mL Kjeldahl digestion flask and 10 mL of distilled water were added to it. Ten milliliters of concentrated H_2SO_4 was added followed by addition of one tablet of selenium and potassium sulphate mixture and 0.10 g of salicylic acid. The mixture was made to stand for 30 minutes and heated mildly to convert any nitrates and nitrites into ammonium compounds. The mixture was then heated more strongly (300 to 350 ^{o} C) to digest the soil to a permanent clear colour. The digest was cooled and transferred to a 100 mL volumetric flask and made up to the mark with distilled water. A 20 ml aliquot of the solution was transferred into a tecatar apparatus allowed to flow into the flask. The distilled ammonium was collected into a 10 mL boric acid, bromocerol green and methyl red solution. The distillate was titrated with 0.01 M HCl solution. A blank digestion, distillation and titration were also carried out as a check against traces of nitrogen in the reagents and water used.

Calculation:

$$\% \mathrm{N} = \frac{(\mathrm{a} - \mathrm{b}) \times 1.4 \times \mathrm{M} \times \mathrm{V}}{\mathrm{sxt}}$$

Where

a = mL HCl used for sample titration,

b = mL HCl used for blank titration,

M = molarity of HCl,

V = total volume of digest,

s = weight of soil taken for digestion in grains,

t = volume of aliquot taken for distillation,

1.4 = 14 x 10^{-3} x 100 % (14 is the atomic weight of N).

- **Available Phosphorus**

Available phosphorus was determined by the Bray P1- method (Bray and Kurtz, 1945). A 2 g of soil sample was extracted with 20 ml of Bray P1 solution (0.03 M NH_4F and 0.025 M HCl). The mixture was shaken on a Stuart reciprocal shaker for 1 minute and immediately filtered through Whatman no. 42 filter paper. A standard series of 0, 1.2, 2.4, 3.6, 4.8 and 6.0 was prepared by pipetting respectively mg P/l 0, 10, 20, 30, 40, 50 ml of 12 mg P l^{-1} into 100 ml volumetric flask and made up to the mark with distilled water. Phosphorus in the sample was determined on a pyeunicam spectrophotometer at a wavelength of 660 nm by the blue ammonium molybdate method with ascorbic acid as the reducing agent.

Calculation:

$$P(mg\ kg^{-1}) = \frac{(a - b)\ x\ Vs\ x\ df}{g}$$

Where:

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

b = mg P L^{-1} in blank;

df = dilution factor;

Vs = the volume of extract and

g = is sample weight in grams.

- **Available potassium**

Available potassium was determined by the method of Sparks et al. (1996). Extraction with 0.1M HCl gives an indication of K in the soil in soluble form, the complex K and the absorbent part of the minerals in the set K. This could be done by the addition of HCl, or by introduction of oxalic acid. By further addition of HCl probably more K would be extracted. This is due to more rapid destruction of minerals by the higher initial acidity. By addition of oxalic acid concentration in H^+ ion remains constant during the extraction and Ca dissolved CaCO3 precipitates as Ca-oxalate.

Calculation:

$$K \text{ in mg } 100 \text{ g}^{-1} \text{ soil} = (a-b),$$

$$K_2O \text{ in mg } 100 \text{ g}^{-1} \text{ soil} = 1.2\ (a-b),$$

Where

a = k ppm measured for sample,

b= K ppm measured for blank.

3.5.7 Determination of yield parameters

Grain yield: 4.29 m^2 in each plot were harvested in the middle of each treatment plot leaving the border rows. The grains were sun dried and their weight were measured and expressed on a hectare basis.

Biomass yield: after the removal of the grain, the above ground biomass was harvested on 4.29 m^2 area and weighed. Sub-samples were collected, saved in plastic bags, weighed and dried at 70 ^{o}C for 48 hours in the laboratory. The dry weight was used to estimate above ground dry matter (ADM) expressed on a hectare basis.

3.5.8. Statistical analysis

The data was analysed using the GenStat statistical package (9^{th} Edition).

3.6. Profitability of land management practices

The VCR was calculated to assess the profitability of the soil management interventions. This was to address the specific objective 4. The unsubsidized input costs and the crop mean prices were used to calculate the VCR as a first indicator of acceptability of investment, using the formula of

Nziguheba et al. (2010): $VCR = \frac{Y-Yc}{x}$

Where

Y= Cost of yield from treatment plot,

Y_c = Cost of yield from the control plot

X = Cost of inputs (seeds and fertilizers).

CHAPTER FOUR

4.0 RESULTS

The results of the study are presented in this chapter with reference to the specific objectives. The results of the four objectives are addressed in sections 4.1 to 4.4

4.1. Delineation and mapping of soil units, vegetation and cropping systems

4.1.1. General overview of the study area and mapping of soil units

The total land area of the study site was 1,163 ha. The village, the plateaux and agricultural land were 7.156 ha (0.61%), 271.81 ha (23.37%), and 884.03 ha (76.01%), respectively. In 2013, 505.6 ha (57.19%) of the arable land were used for crop production. Figure 4.1: showed the geographic extent of the study area.

The pre-processing, especially radiometric enhancement (neighbourhood 3x3) brought out the contrasts on the Landsat image and facilitated the identification of 25 soil units and the village (Figure 4.2).

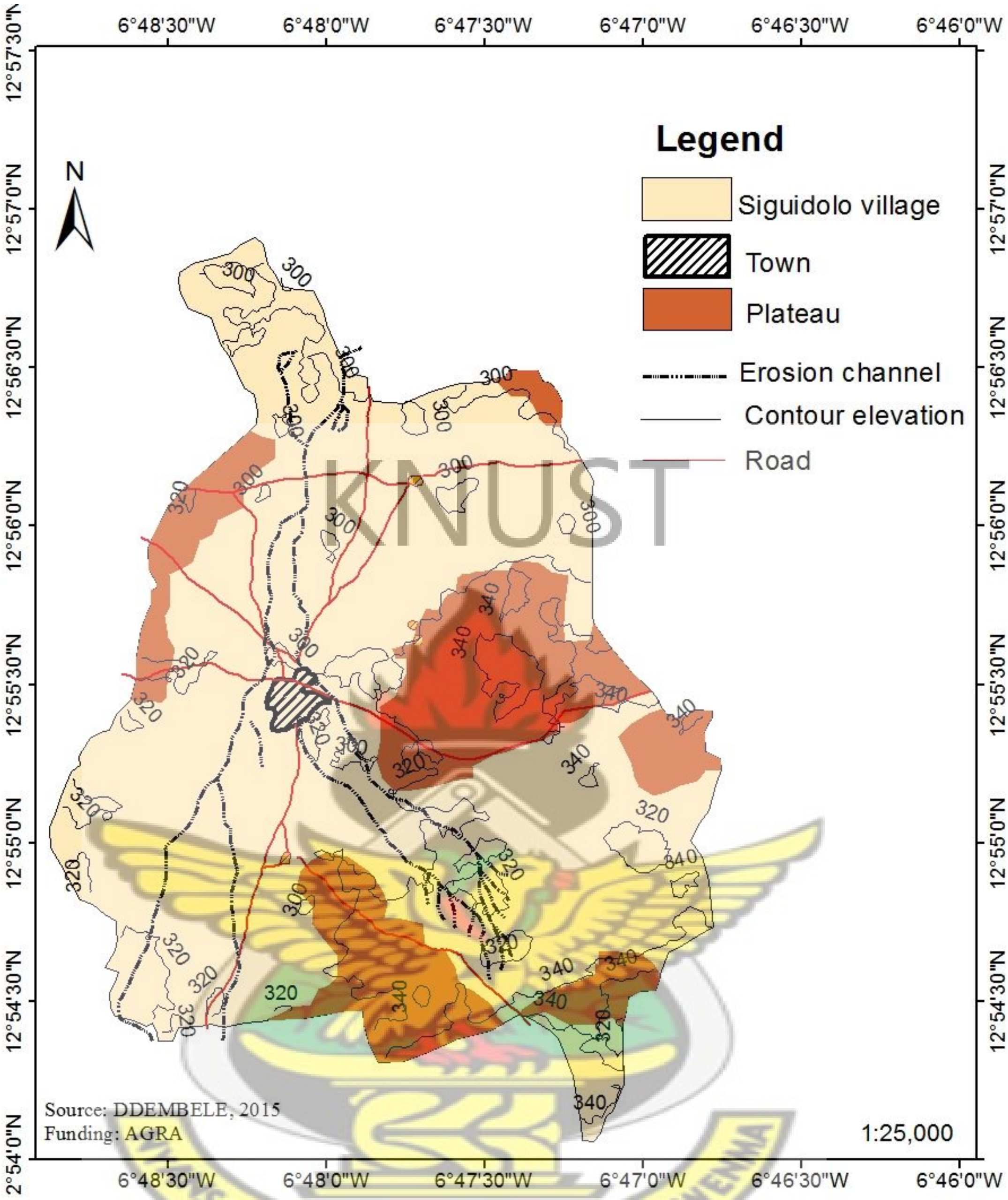

Figure 4.1: Map of the Siguidolo area (study site) in 2013

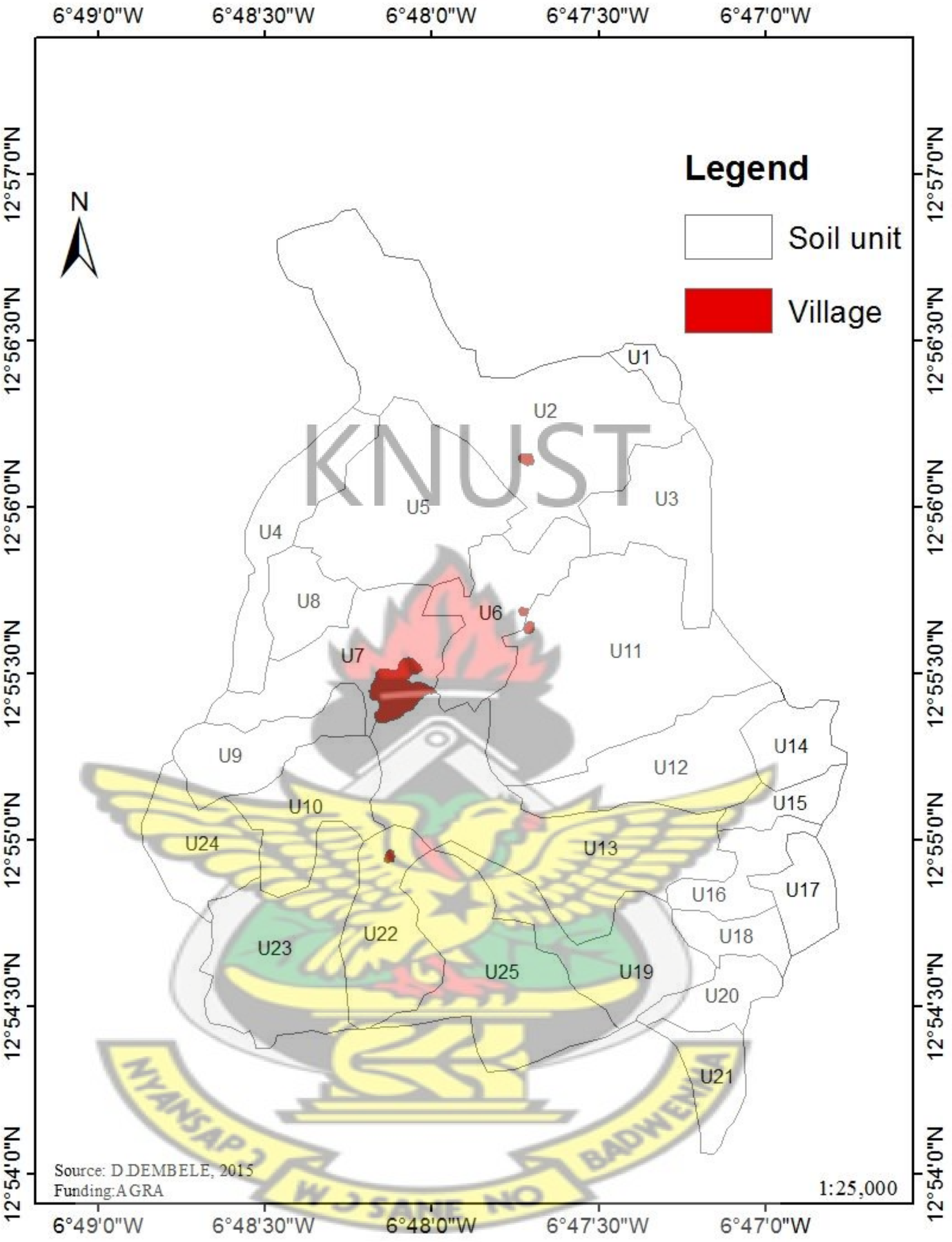

Figure 4.2: The spatial distribution of soil units at Siguidolo

4.1.2 Delineation and mapping of vegetation:

The vegetation, derived from the NDVI values, is presented in Figure 4.3. The best image for NDVI calculation covered 75.5% (878.2 ha) of the study area. The vegetation index values ranged from -0.01 to 0.24 which were classified into bare soil (-0.01 - 0.02), grassland with scattered trees (0.02 - 0.05), and woodland with grass cover (0.05 - 0.24).

The bare soil covered 278.26 ha (31.69%) of the area. The grassland with scattered trees occupied 451.01 ha (51.36%) and comprised grasses, such as *Andropogon guayanus,* crop residues and shrubs, such as *Piliostigma reticulatum*. The woodland had an areal extent of 148.93 ha (16.62%) and consisted of green vegetation including *Vitellaria paradoxa, Parkia biglobosa, Adansonia digitata, Tamarindus indica L., Lannea microcarpa and Lannea acida Piliostigma reticulatum* on the bottom of the toposequence then *some Lannea microcarpa and acida, Zizziphus mauritiana, Guiera senegalensis, Combretum micranthum, Combreton glutinosiun, Bauhinia rufescens, Bauhinia reticulate, Pennisetum pedicelatum,* on the top of the toposequence.

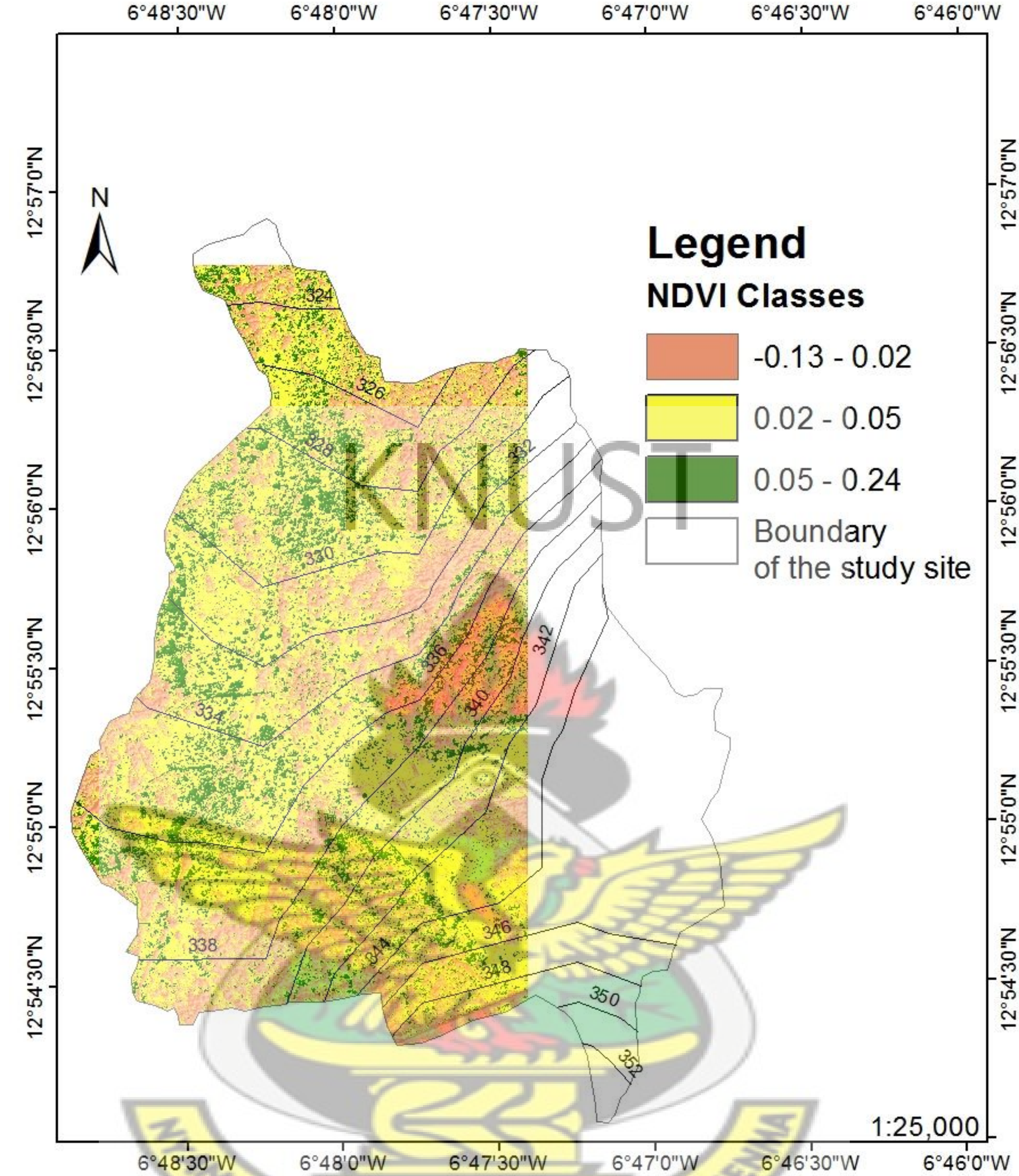

Figure 4.3: NDVI of the study area from Quick bird image in 2013

4.1.3. Cropping systems analysis and mapping

The cropping system maps of the study area were produced from GPS data in a GIS domain. The three-year maps facilitated the trend in cropping system from 2011 to 2013 (Figures 4.4, 4.5 and 4.6). The crops comprised sorghum, millet, cotton, maize, vegetables (gardening), peanut, cowpea, roselle, as sole, intercrops of sorghum-cowpea, maize-sorghum, millet-peanut, millet-cowpea and fallow land. Table 4.1 and 4.2 give the areas covered by these crops in absolute terms (ha) and as percentage of the total arable land.

In order to assess the changes in cropping system and area covered over the years, the 2011 values were used as the baseline (Table 4.2).

In all the years, sole sorghum and millet occupied the greatest area of the arable land. However, the area under sorghum consistently declined in 2012 and 2013 by 30.3 and 32.4 per cent. Millet on the other hand increased by 3.4% in 2012 but declined by 5.3% in 2013. Maize tended to increase by 47.1 and 34.1 per cent in 2012 and 2013 respectively. Sorghum-maize intercrop increased by 39.5% in 2013 but was not practised in 2013.

The changes in the area covered by the cereals were accompanied by a shift towards cereal-legume intercrops. The base area coverage by millet-peanut in 2011 increased by 84.5 and 81.2 per cent in 2012 and 2013 respectively. The corresponding increases in sorghum-cowpea intercrop were 45.3 and 61.0 per cent. Sole peanut and cowpea do not appear to be popular in the area. Vegetable production was also enhanced with increases in the cultivated area of 24.8 and 7.1 per cent in 2012 and 2013 respectively.

Cotton production in Siguidolo also declined progressively by 27.2% in 2012 and 38.1% in 2013. It is worth indicating that cotton production is commonly accompanied by cotton-cereal rotation such as cotton-maize, cotton-sorghum and cotton-millet. The change in fallow area was not significant.

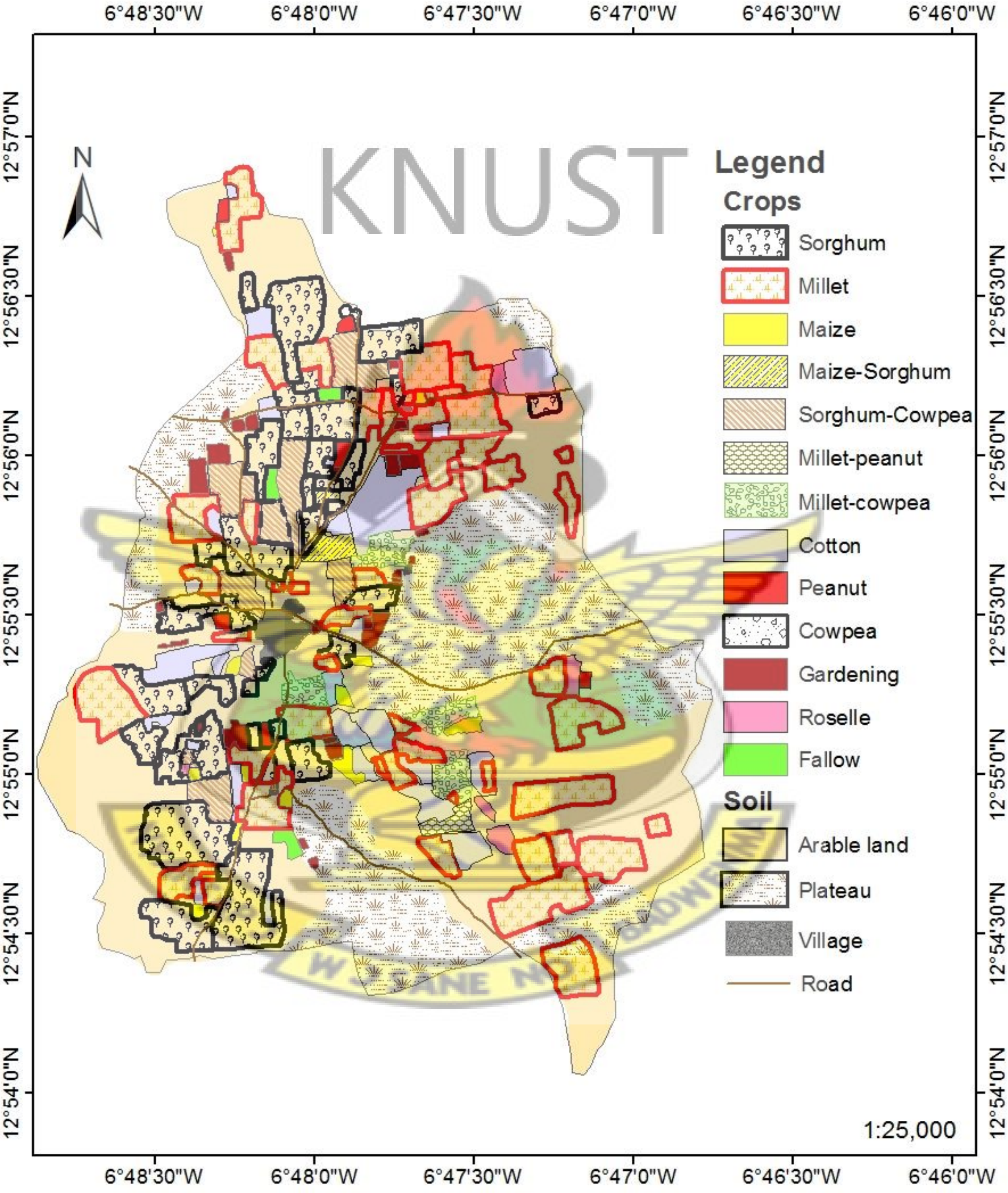

Figure 4.4: Spatial distribution of cropping systems in 2011

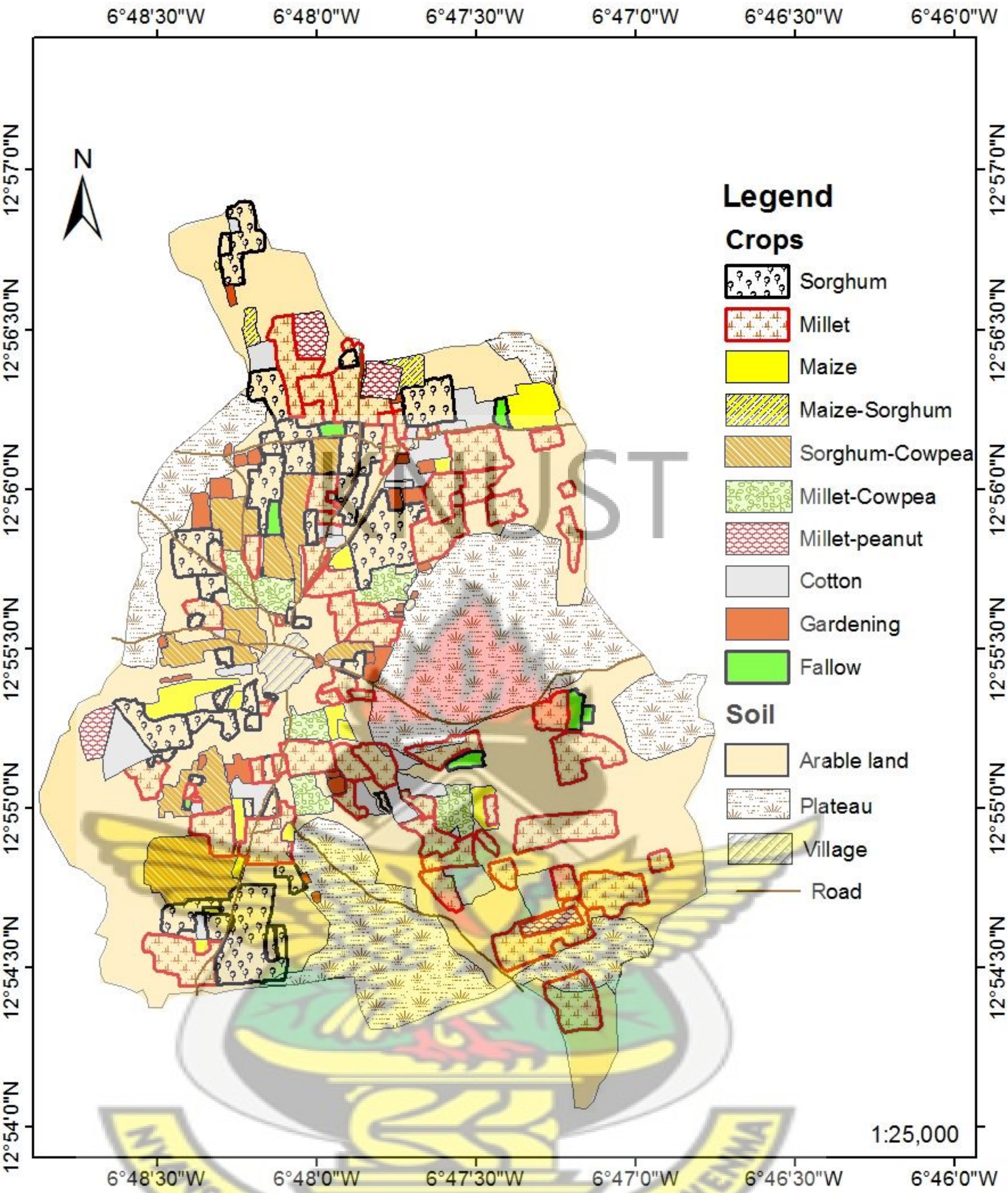

Figure 4.5: Spatial distribution of cropping systems in 2012

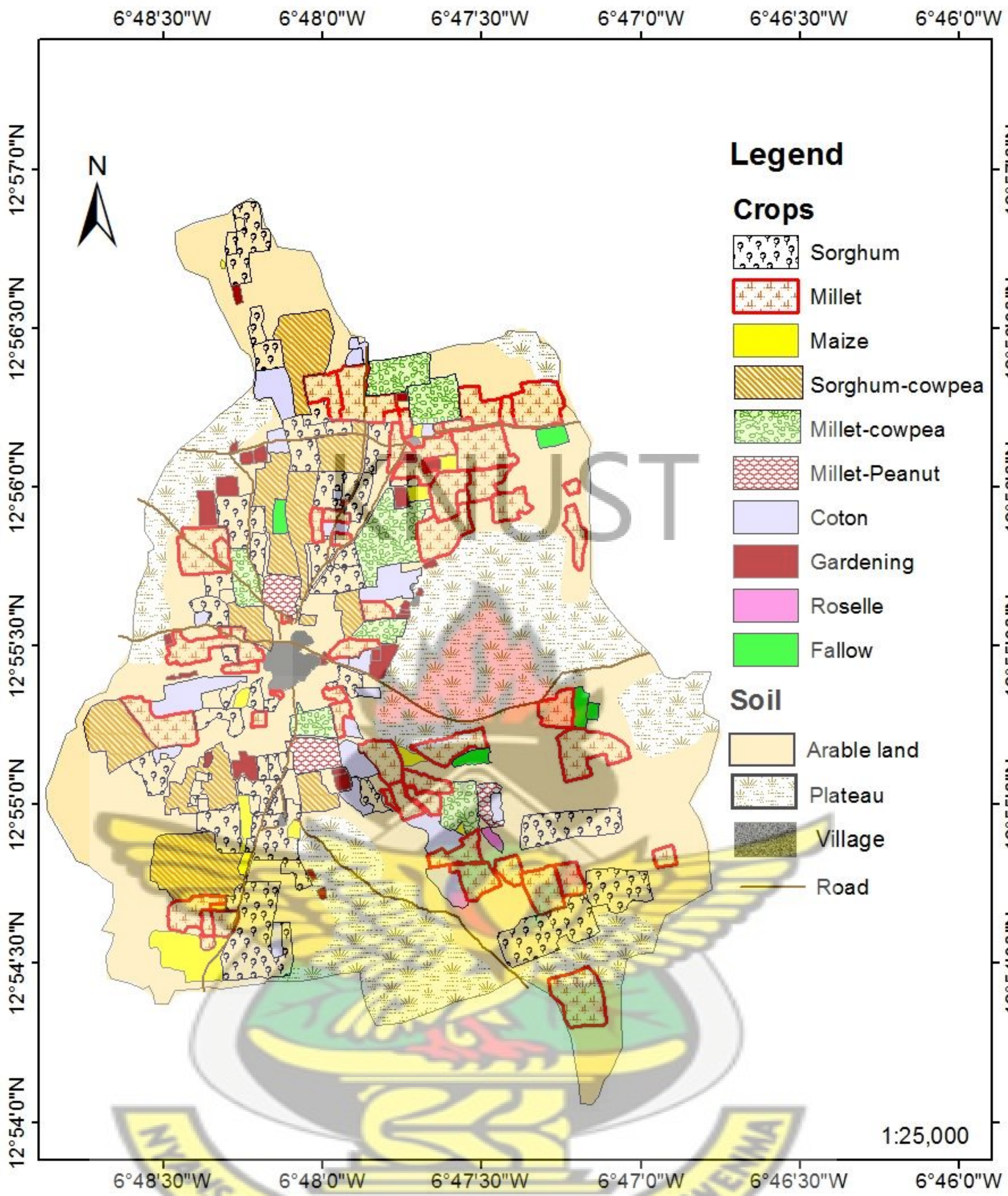

Figure 4.6: Spatial distribution of cropping systems in 2013

Table 4.1: changes in cropping areas from 2011-2013

Crops	Area (ha) 2011	2012	2013
Cotton	65.3	47.57	40.4
Sorghum	164.12	114.37	110.97
Millet	175.46	181.70	166.22
Maize	10.05	19	15.25
Gardening	15.8	21	17
Millet-peanut	3.29	21.18	17.5
Millet-cowpea	18.54	26.99	48.57
Sorghum-cowpea	31.63	57.80	81.03
Sorghum-Maize	5.14	8.5	0
Roselle	6.16	0	1.5
Fallow	7.52	7.60	7.38
Peanut	1.64	0	0
Cowpea	1.06	0	0
Total	505.71	505.71	505.71

Table 4.2: Percentage of cropping areas from 2011 to 2013

Crops	Area (%) 2011	2012	2013
Cotton	12.91	9.41	7.99
Sorghum	32.45	22.62	21.94
Millet	34.70	35.93	32.87
Maize	1.99	3.76	3.02
Vegetable (Gardening)	3.12	4.15	3.36
Millet-peanut	0.65	4.19	3.46
Millet-cowpea	3.67	5.34	9.60
Sorghum-cowpea	6.25	11.43	16.02
Sorghum-Maize	1.02	1.68	0
Roselle	1.22	0	0.30
Fallow	1.49	1.50	1.44
Peanut	0.32	0	0
Cowpea	0.21	0	0
Total	100	100	100

4.2 Assessment and mapping of soil physical and chemical properties

4.2.1 Soil physical properties and mapping

Soil texture was the main physical property assessed. These comprised clay, silt and sand at the 0-20 cm depth referred to as the topsoil

. 4.2.1.1 Clay content

The clay content of the topsoil is presented in Figure 4.7. Clay percentage ranged from 1.22% to 12% classified as 1.22- 4.51%; 4.51-8.11%; and 8.11 - 12% with their respective area of coverage as 363.66 ha (41.13%), 459.25 ha (51.95%) and 60.87 ha (6.88%).

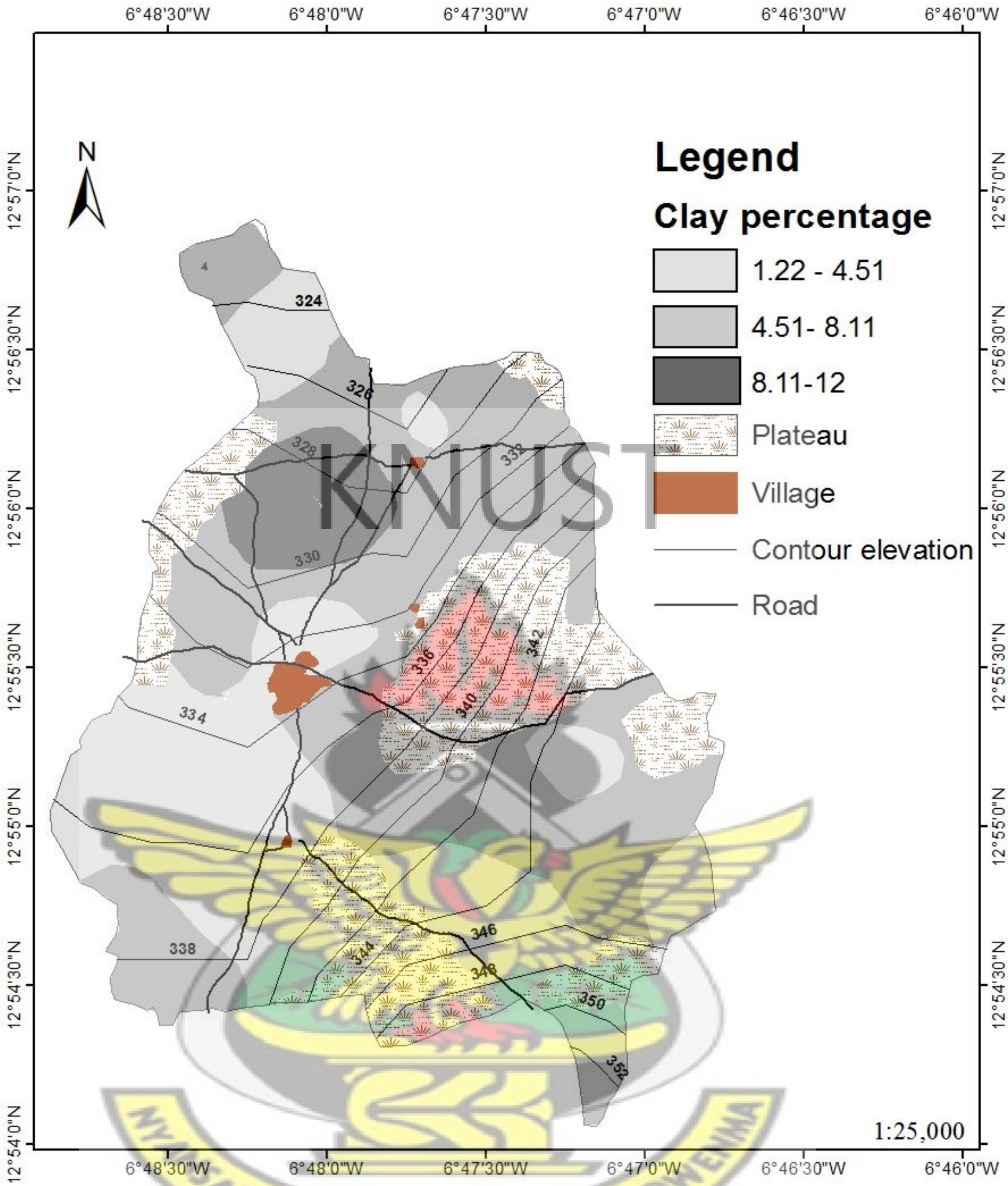

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Figure 4.7: Spatial distribution of clay at Siguidolo in 2013

4.2.1.2 Silt content

Figure 4.8 illustrates silt content in the study area. Silt percentage was between lowest of 16% and highest of 40.44%. These were categorized into class 16 -22.30%; 22.30 - 33.50%; and 33.50- 40.44% for mapping purposes. Their respective area of coverage were 405.2 ha (45.83%), 233.46 ha (26.19%) and 231.87 ha (26.01%) respectively.

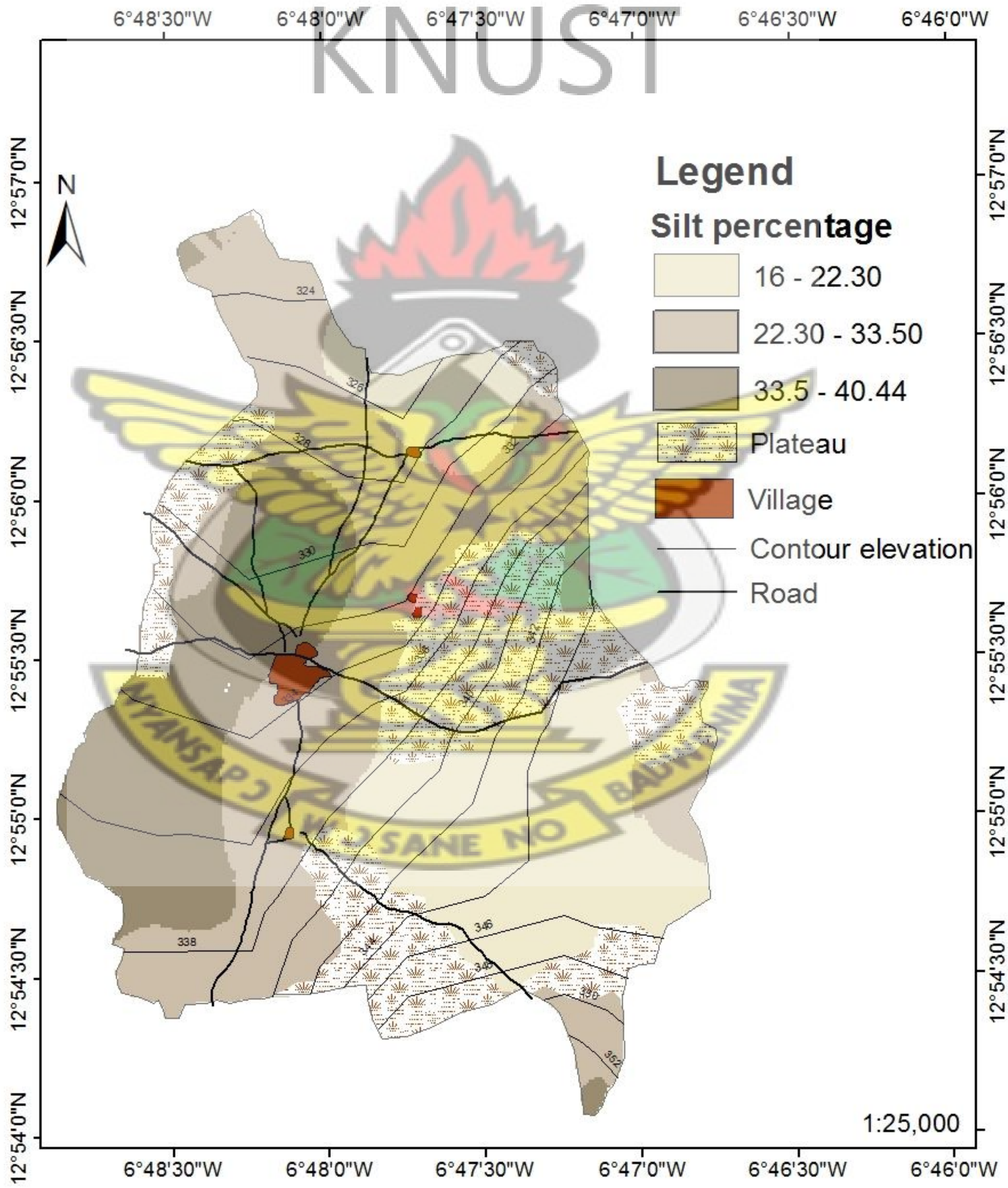

Figure 4.8: Spatial distribution of silt at Siguidolo in 2013

4.2.1.3. Sand content

Sand content is presented in Figure 4.9. The percentage of sand ranged from a lowest of 46.52% to a highest of 85%. The lowest sand content 46.52 - 59.28% was found on 173.2 ha (19.59%); 59.28 - 71% was observed on 325.69 ha (36.84%) and 71 - 85% was on 384.79 ha (43.56%).

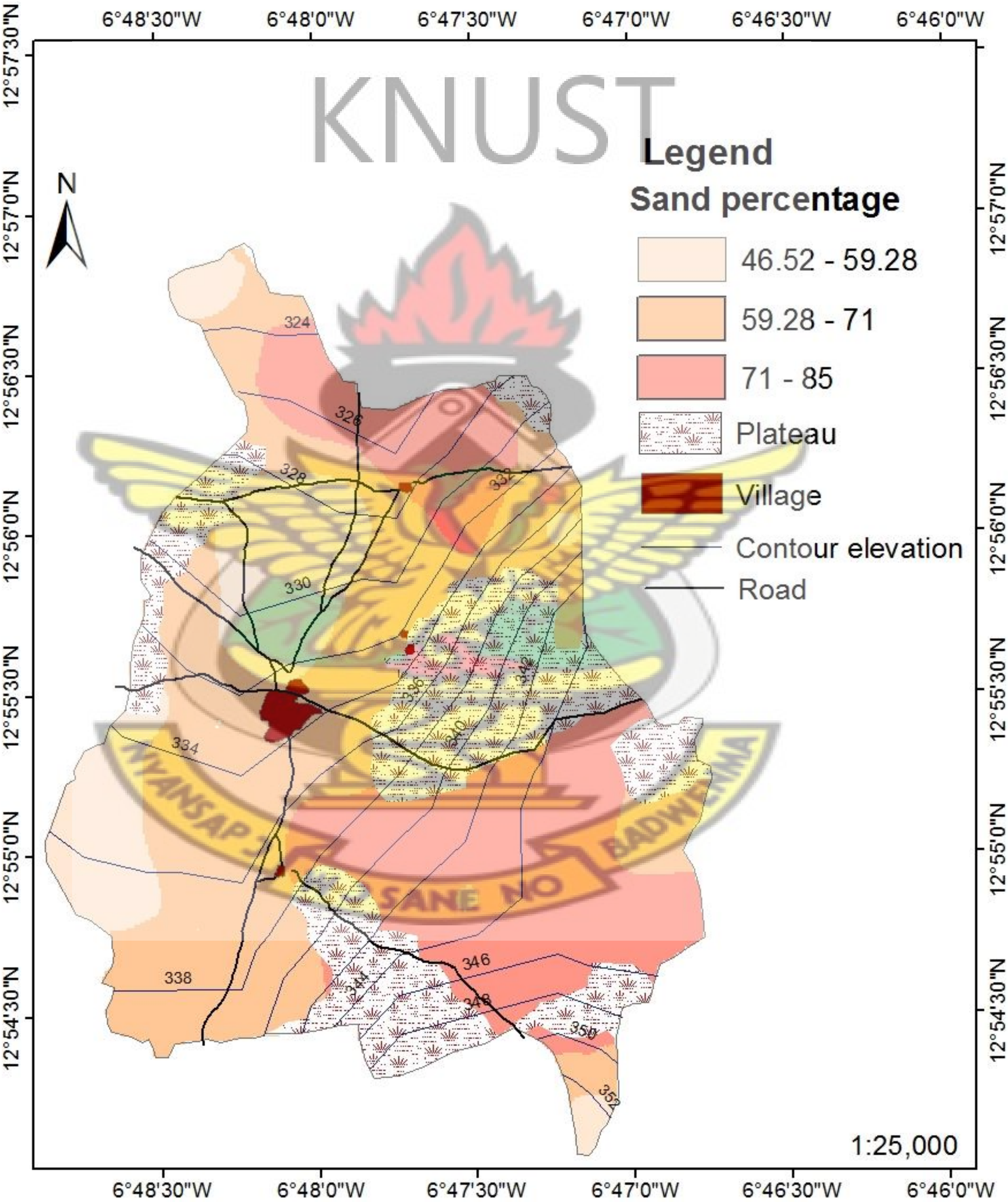

Figure 4.9: Spatial distribution of sand at Siguidolo in 2013

4.2.1.4. Soil texture

Figure 4.10 shows the geographic location of soil textures and their spatial distribution at Siguidolo. The texture comprised: loam, loamy sand, sandy loam, and sand which occupied 78.21 ha (8.84%), 68.99 (7.80%), 689.06 ha (77.94%) and 47.40 ha (5.42%) respectively. The main soil texture observed in the area was sandy loam. The experimental field for studying the impact of soil amendments was therefore sited on the sandy loam soil to facilitate and enhance the usefulness of the results for the greater part of the study area.

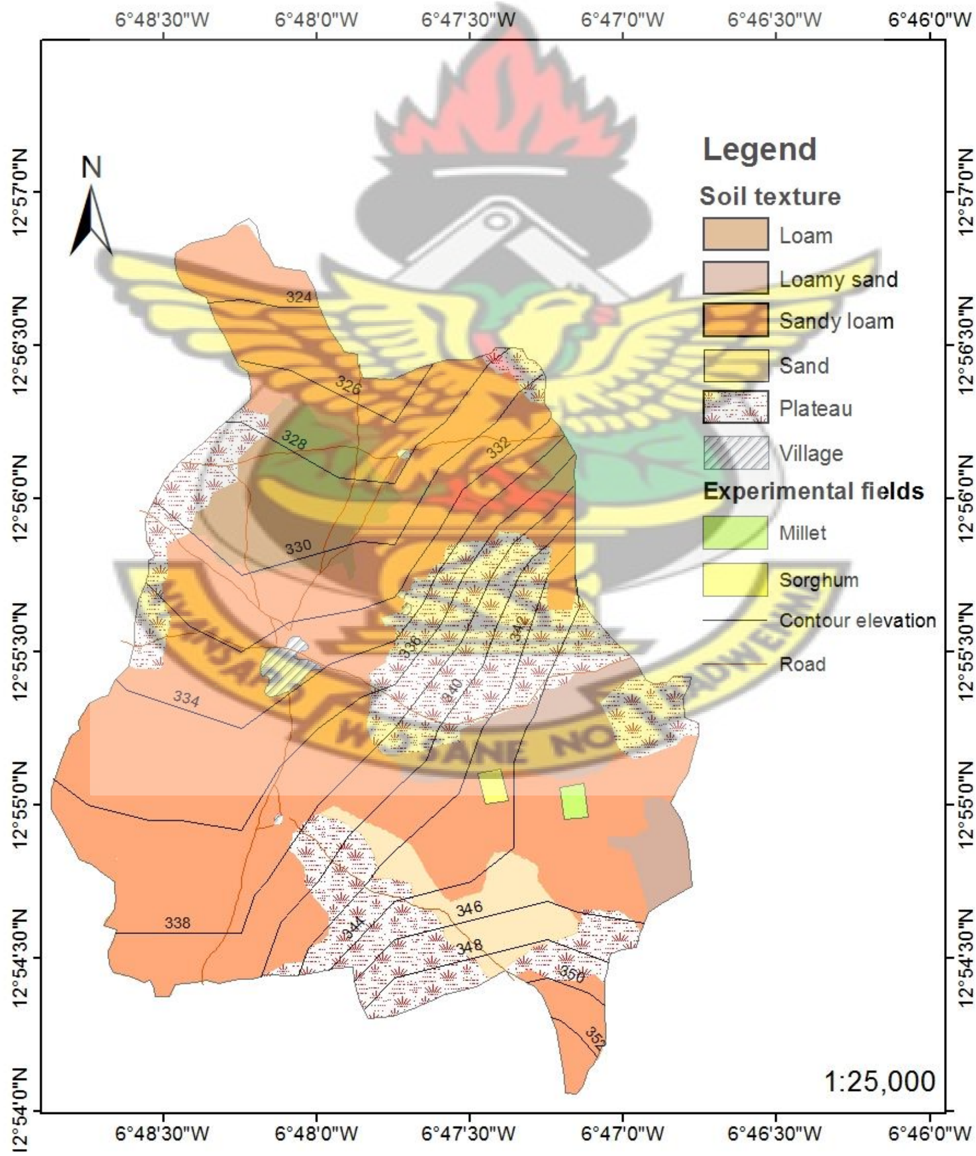

Figure 4.10: Spatial distribution of soil texture at Siguidolo in 2013

4.2.2 Assessment and mapping of soil chemical properties

4.2.2.1 Spatial structure and variability of soil chemical properties

Table 4.3 shows the results of the basic statistical analysis of the selected soil parameters. The mean values give the general magnitude of the measured parameters at the site. Of great importance to the development of sustainable land management strategies are the measures of variability in the measured values and their dispersion about the mean. These include the coefficient of variation, skewness and kurtosis. The CV ranged from a low of 5.54% for pH to a high of 92.2% for C, Total N, P and K presented variable intermediate values from 29.81% to 60.1%. The skewness values were positive for C, N, P and K and negative for pH. These values have implications for the magnitude of most values relative to those of extreme values and their spread about the mean. Kurtosis, on the other hand, indicates the degree of dispersion about the mean depending on whether it is less (< 0) (highly dispersed) or greater (> 0) (less dispersed) than zero. The former and the latter classes covered C, N and K; and pH and P respectively.

The data were further subjected to Anderson Darling test for normal distribution to satisfy the requirements for kriging. The transformed data are presented in appendices 3, 4, 5 and 6 for C, N, P and K respectively and appendix 2 for pH which did not need any transformation. The figures show the mean, standard deviation and the probability values of the mean parameters

Table 4.3: Results of basic statistical analysis for the selected soil parameters

Soil nutrient	**pH**	**C %**	**TN %**	**Avail P Mg kg^{-1}**	**K Cmolc kg^{-1}**
Mean	5.47	0.15	0.016	3.76	0.02
Median	5.48	0.10	0.02	3.68	0.02
Minimum	4.70	0.01	0.00	1.38	0.01
Maximum	6.22	0.50	0.03	7.11	0.05
Coefficient of variation (CV)	5.54	92.20	43.72	29.81	60.61
Standard deviation	0.30	0.14	0.007	1.12	0.01
Skewness	-0.26	0.58	0.33	0.40	0.58
Kurtosis	0.44	-0.92	-0.54	0.76	-1.29

In order to generate the spatial structure of the selected soil parameters, semivariograms were calculated. According to ESRI (2010), a semivariogram is one of the significant functions to indicate spatial correlation in observations measured at sample locations. It is commonly represented as a graph that shows the variance in the measured parameters relative to the distance between all pairs of sampled locations. In this study several models were tested and the best that described the spatial structures were chosen. Gaussian and exponential models were the best. The spatial variations identified by the semivariogram models are presented in Table 4.4 with the respective for pH, C, N, P, and in Figures 4.11, 4.12, 4.13, 4.14 and 4.15.

The Table 4.4 shows the parameters of semivariogram models generated. The Gaussian and exponential models were used. The nugget ranged from highest 0.310 for available phosphorus to lowest 0.0002 for potassium. The sill oscillated between a highest of 1.061 for available phosphorus to a lowest of 0.0005 for potassium. The range, with values between 1185.47 to 2090 m, ranked in decreasing order of K > N > C > P > pH. The ratio of nugget/sill was in the order of total nitrogen >

exchangeable potassium > pH > available phosphorus > SOC with a range of 16.6 to 140.5%. The spatial dependence was strong for SOC, medium for soil pH, soil available phosphorus and soil exchangeable potassium and weak for soil total nitrogen.

Table 4.4: Parameters of semivariogram models for the study

Soil nutrients	Theoretical Model	Nugget (Co)	Sill (Co+C)	Range (A) (m)	(Co/Co+C) (%)	Spatial dependence
pH	Gaussian	0.023	0.072	1185.47	31.9	Medium dependence
Carbon (%)	Exponential	0.003	0.018	1793.37	16.6	Strong dependence
Total Nitrogen (%)	Exponential	0.111	0.079	1994.2	140.5	Weak dependence
Av. Phosphorus (mg kg^{-1})	Exponential	0.310	1.061	1248.80	29.2	Medium dependence
Exh. Potassium ($cmol_c$ kg^{-1})	Exponential	0.0002	0.0005	2090	40	Medium dependence

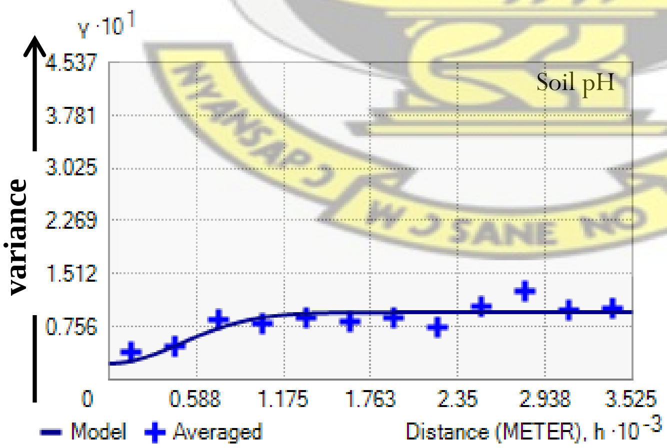

Figure 4.11: Semivariogram for soil pH

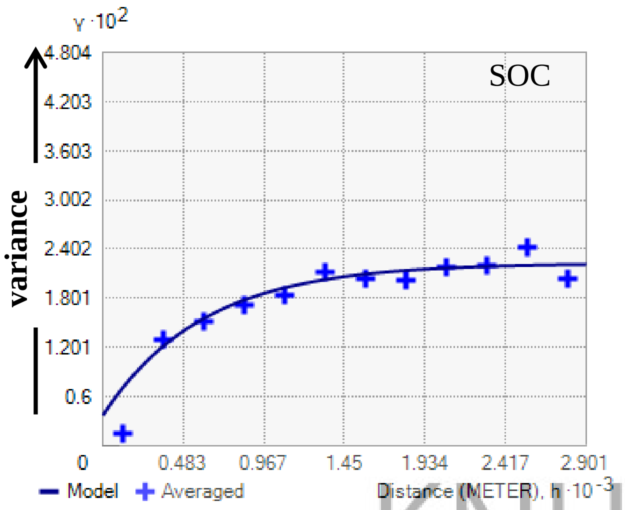

Figure 4.12: Semivariogram for soil organic carbon

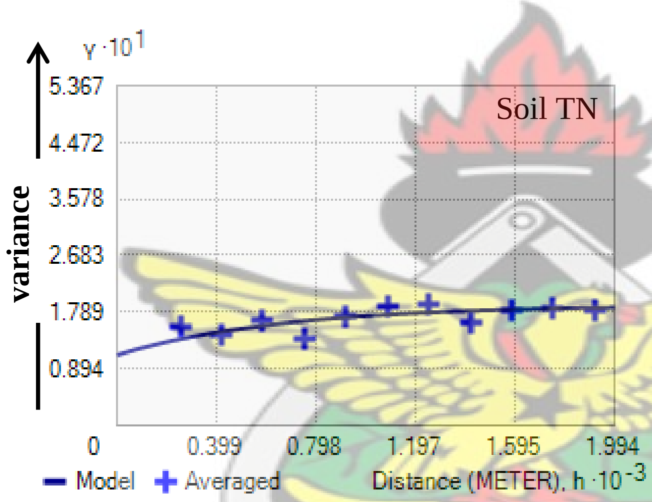

Figure 4.13: Semivariogram for soil total nitrogen

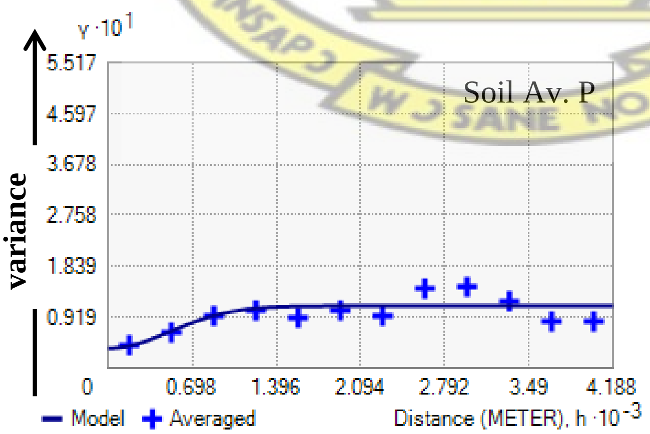

Figure 4.14: Semivariogram for soil available phosphorus

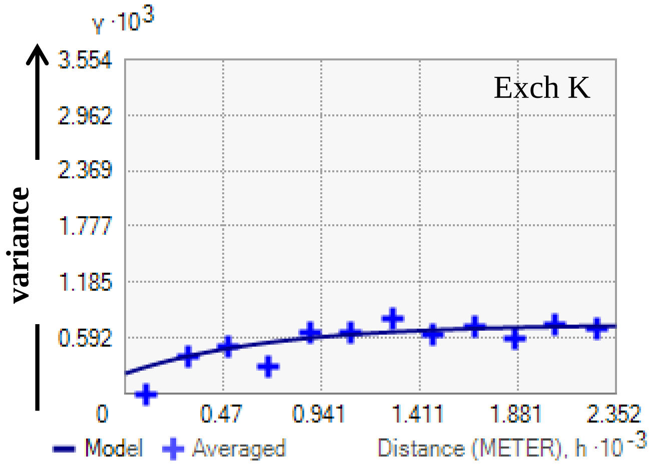

Figure 4.15: Semivariogram for soil exchangeable potassium

4.2.2.2. Spatial distribution of soil pH

Figure 4.16 shows the spatial distribution of soil pH at Siguidolo in 2013. Soil pH ranged from 4.7 to 6.1, and grouped into three classes with their respective area of coverage as 82.03 ha (9.28%), 542.62 ha (61.38%) and 259.38 ha (29.34%). These values varied from very strongly acid to moderately acid (Landon, 1994). The strongly acid (4.7 to 5.5) covered 624.65 ha (70.66%) of the arable land. The prediction equation for the unsampled locations (Y) was: Y=0.58pH + 2.30.

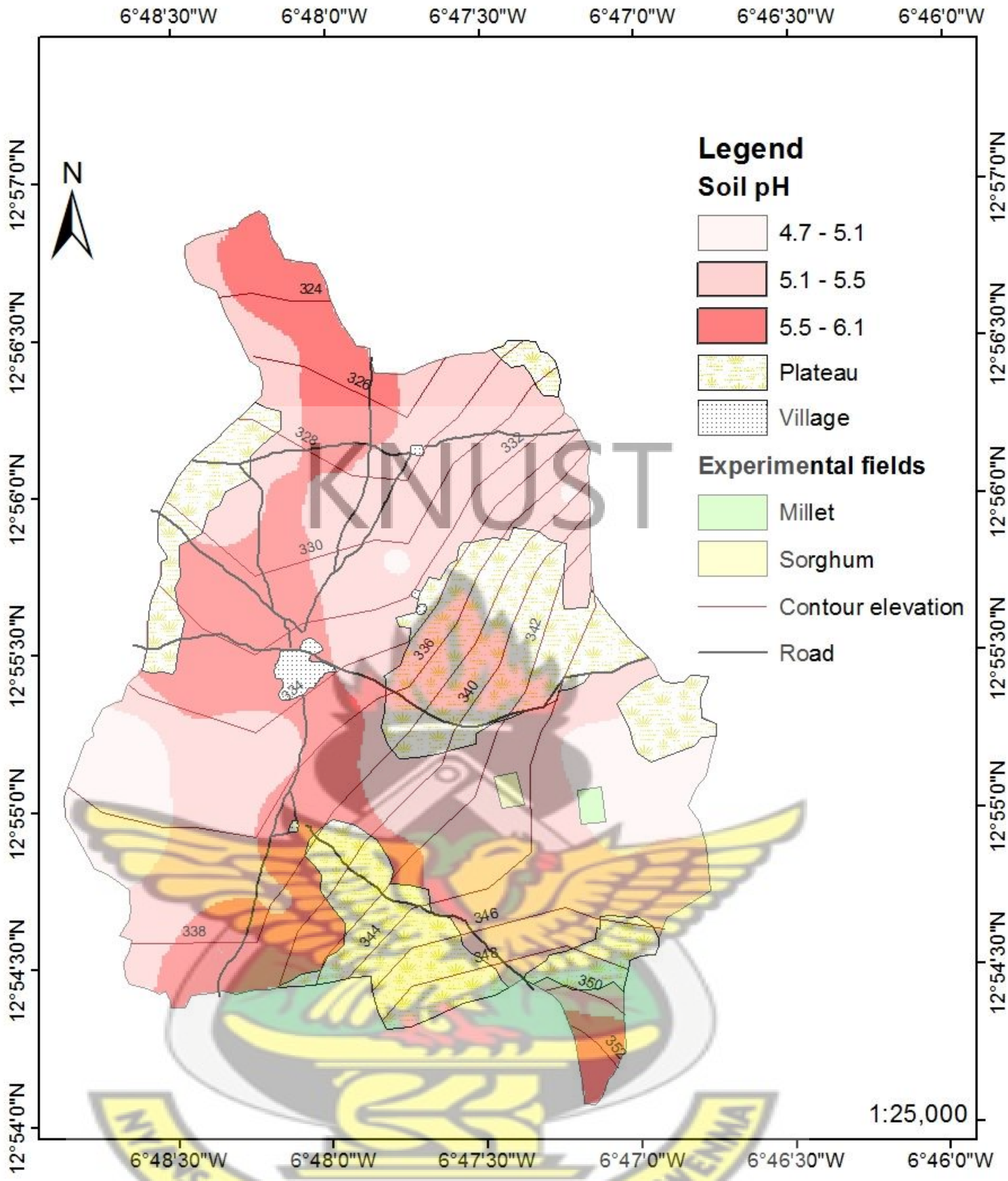

Figure 4.16: Spatial distribution of soil pH at Siguidolo in 2013

4.2.2.3. Spatial distribution of SOC

Figure 4.17 presents the spatial distribution of soil organic carbon content in Siguidolo in 2013. SOC ranged from 0.12 to 0.4%. The three classes of negligible to 0.12%; 0.12 to 0.23%; and 0.23- 0.42% covered 371.50 ha (42.02%); 289.32 ha (32.72%) and 223.34 ha (25.26%) respectively. The predicted equation for the unsampled location (Y) was Y=0.28C + 0.11.

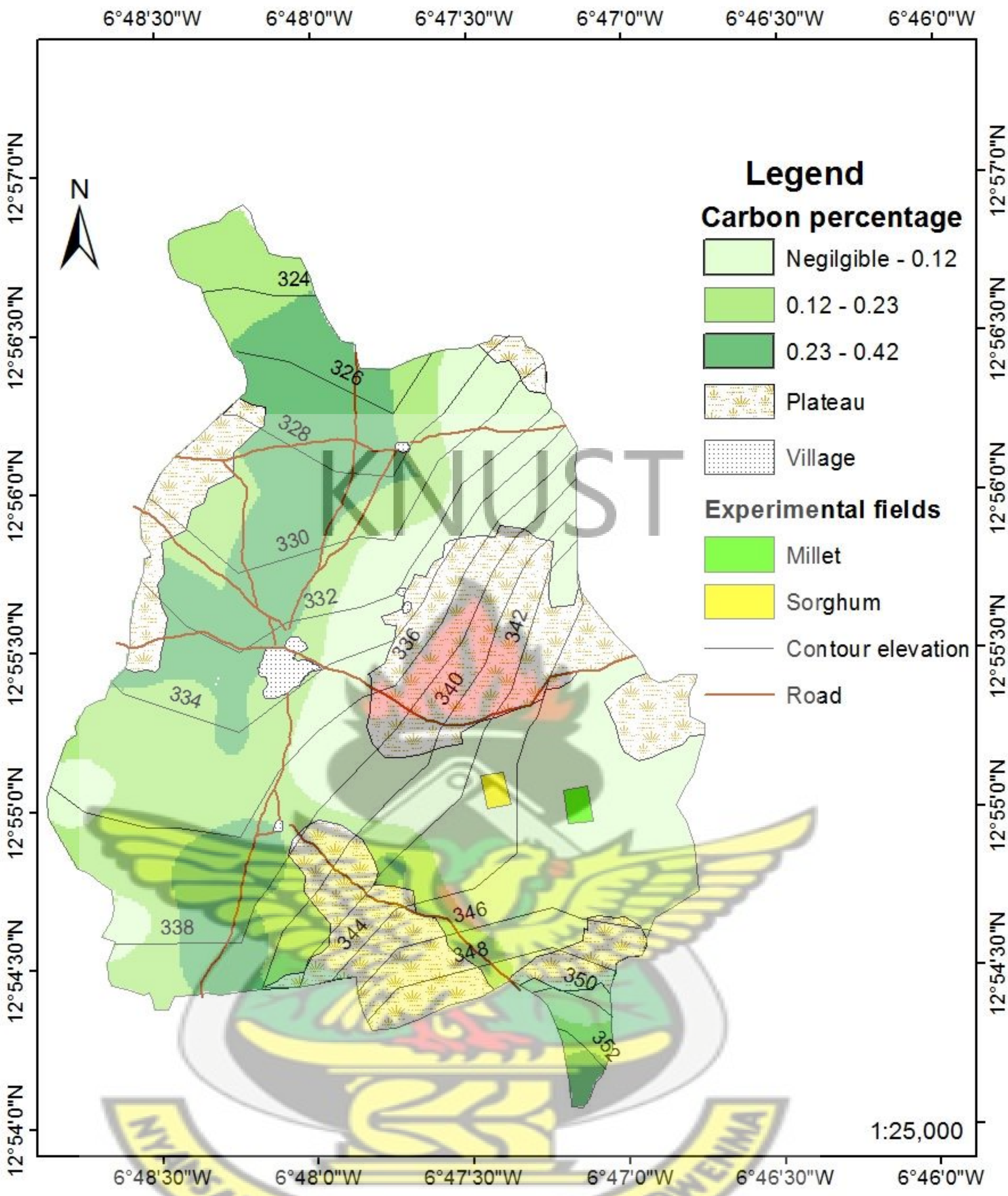

Figure 4.17: Spatial distribution of soil organic carbon at Siguidolo 2013

4.2.2.4. Spatial distribution of soil total nitrogen

The different levels and distribution of total nitrogen in 2013 are presented in Figure 4.18. The percentage of total nitrogen content was very low. It ranged from negligible to 0.03%. The 3 classes, negligible to 0.01%; 0.01 to 0.02% and 0.02 to 0.03% occupied 325.17 ha (36.78%); 239.19 ha (27.05%) and 320.05 ha (36.20%) of the arable area, respectively. The equation for the prediction of the unsampled locations was Y=0.12N + 0.01.

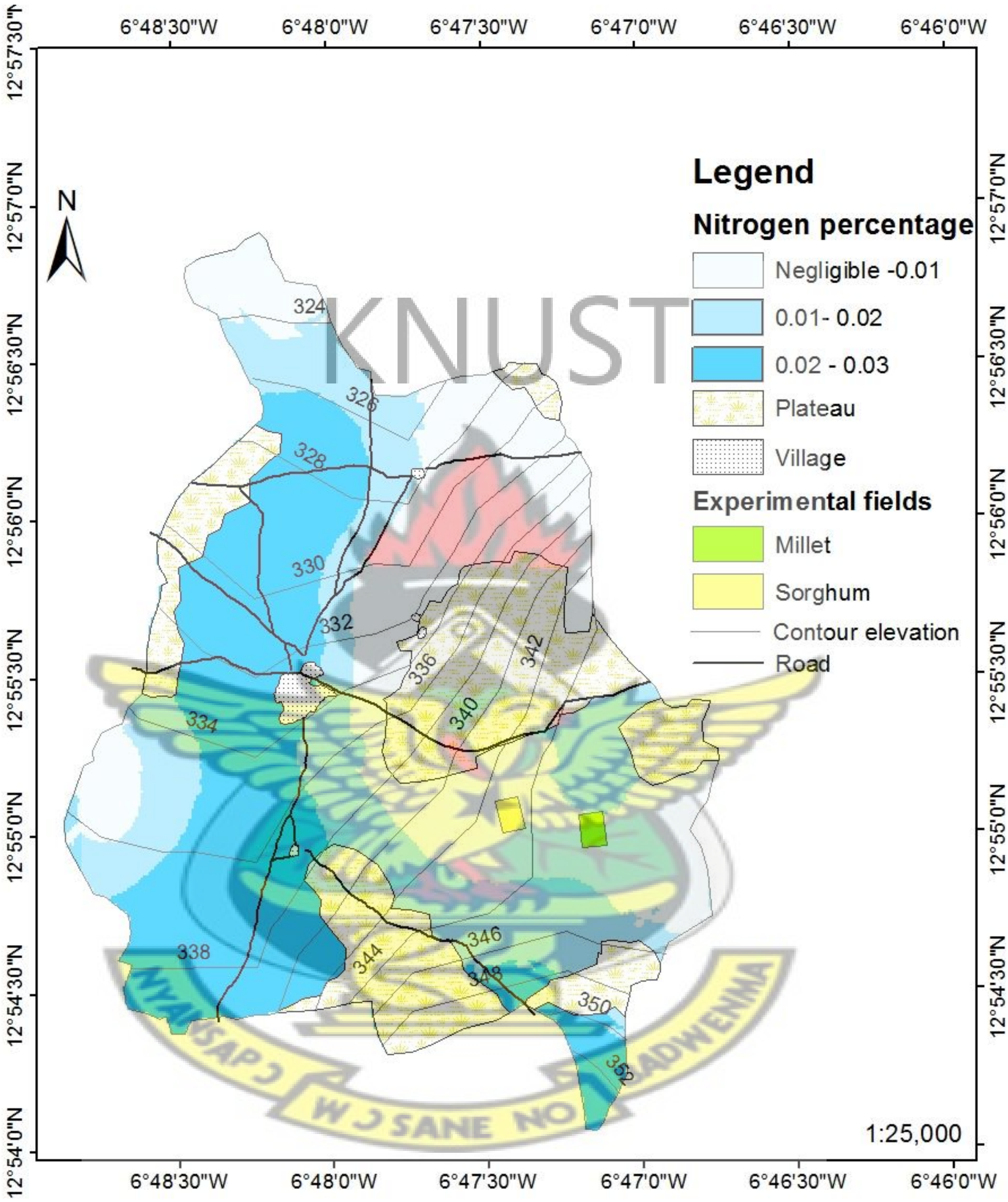

Figure 4.18: Spatial distribution of total nitrogen at Siguidolo in 2013

4.2.2.5. Spatial distribution of available phosphorus

The spatial distribution of available phosphorus of the top soil is presented in Figure 4.19. The available phosphorus ranged from 2.22 to 5.51 mg/kg. These were categorized into 2.22- 3.39 mg/kg on 256.7 ha (29.03%), 3.39-4.26 mg/kg on 464.97

ha (52.37%) and 4.26- 5.51 mg/kg on 164.43 ha (18.60%) of the arable land. The predicted equation for the unsampled location was Y=0.45P + 2.05.

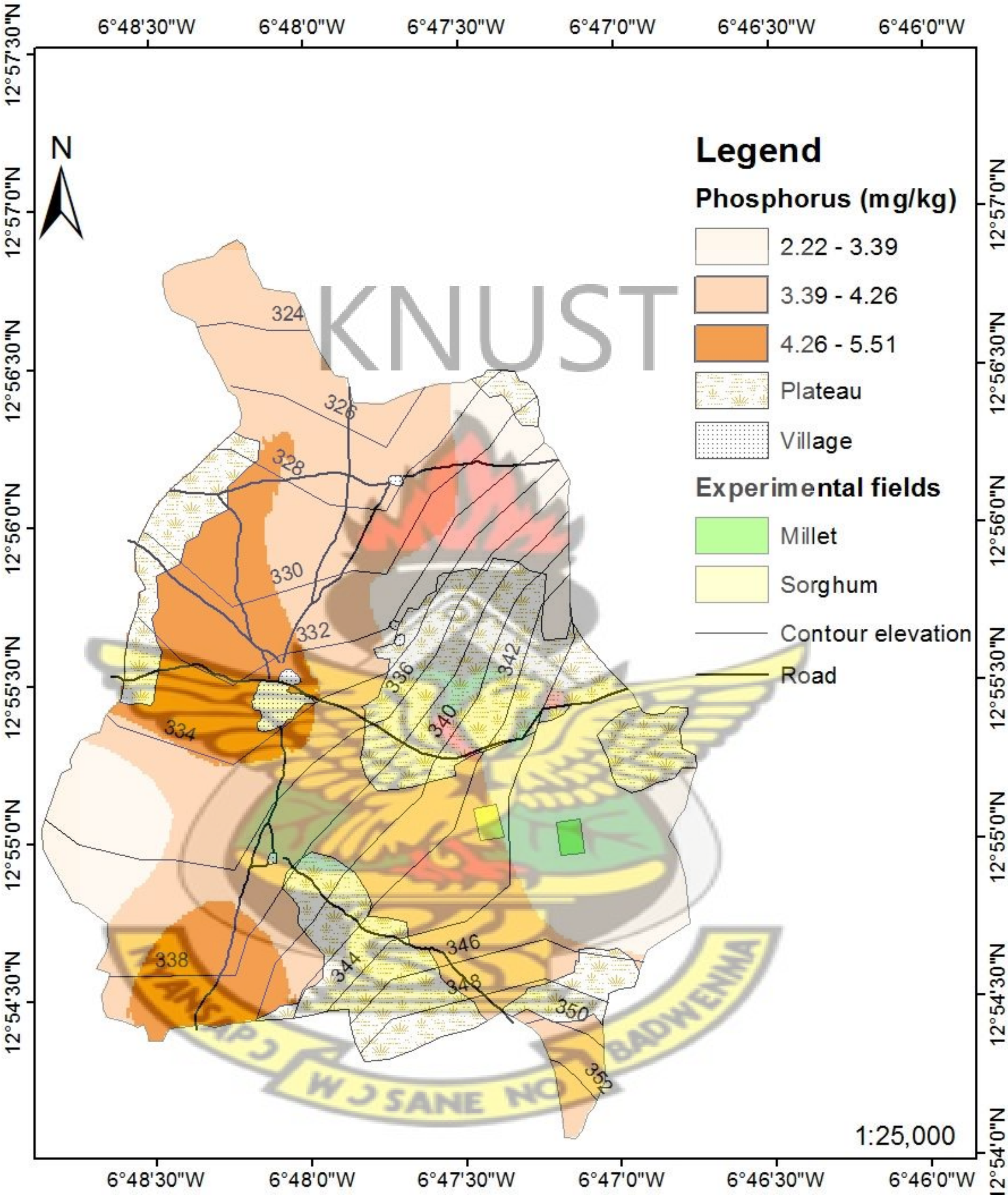

Figure 4.19 Spatial distribution of available phosphorus at Siguidolo in 2013

4.2.2.6 Spatial distribution of exchangeable potassium

Potassium levels and their spatial distribution are presented in Figure 4.20. The soil K status varied from 0.01 to 0.07cmol$_c$ kg^{-1}. The three classes for mapping were 0.01-0.02 cmol$_c$ kg^{-1} covering 593.15 ha (67.09%) followed by 237.15 ha (26.82 %)

and 53.91 ha (6.09 %) for 0.02 to 0.04 $cmol_c\ kg^{-1}$ and 0.04 to 0.07 $cmol_c\ kg^{-1}$ respectively. The predicted equation for the unsampled location was: Y= 0.21K + 0.02.

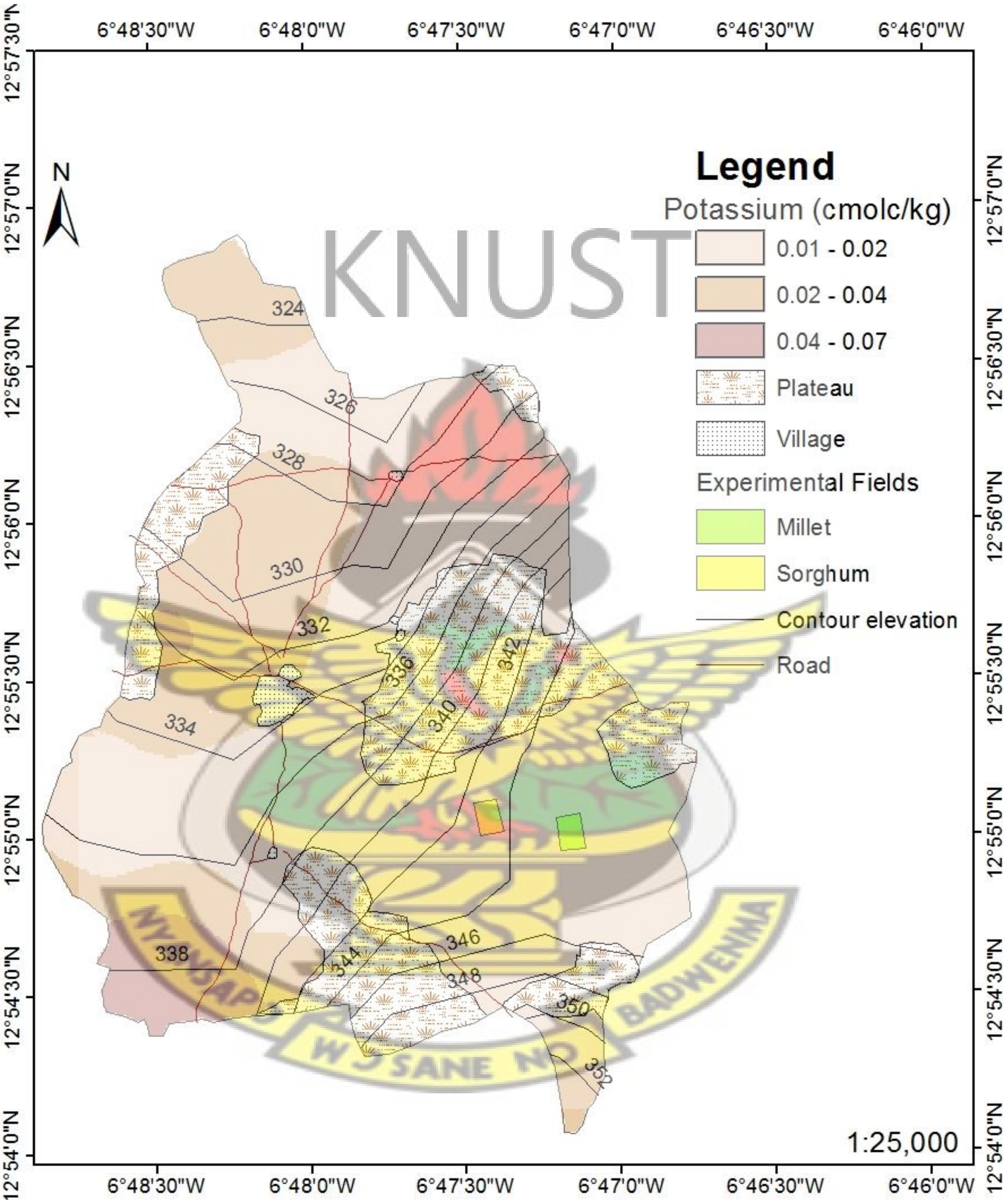

Figure 4.20: Spatial distribution of exchangeable potassium at Siguidolo in 2013

4.2.2.7. Soil fertility map

The superimposition of carbon, total nitrogen, available phosphorus and potassium generated a soil fertility status map of the study area (Figure 4.21). The area was delineated into three soil fertility classes namely low, very low and extremely low. Their respective area of coverage were 42.54 ha (4.81%), 706.61 ha (79.93%) and 134.9 ha (15.26%).

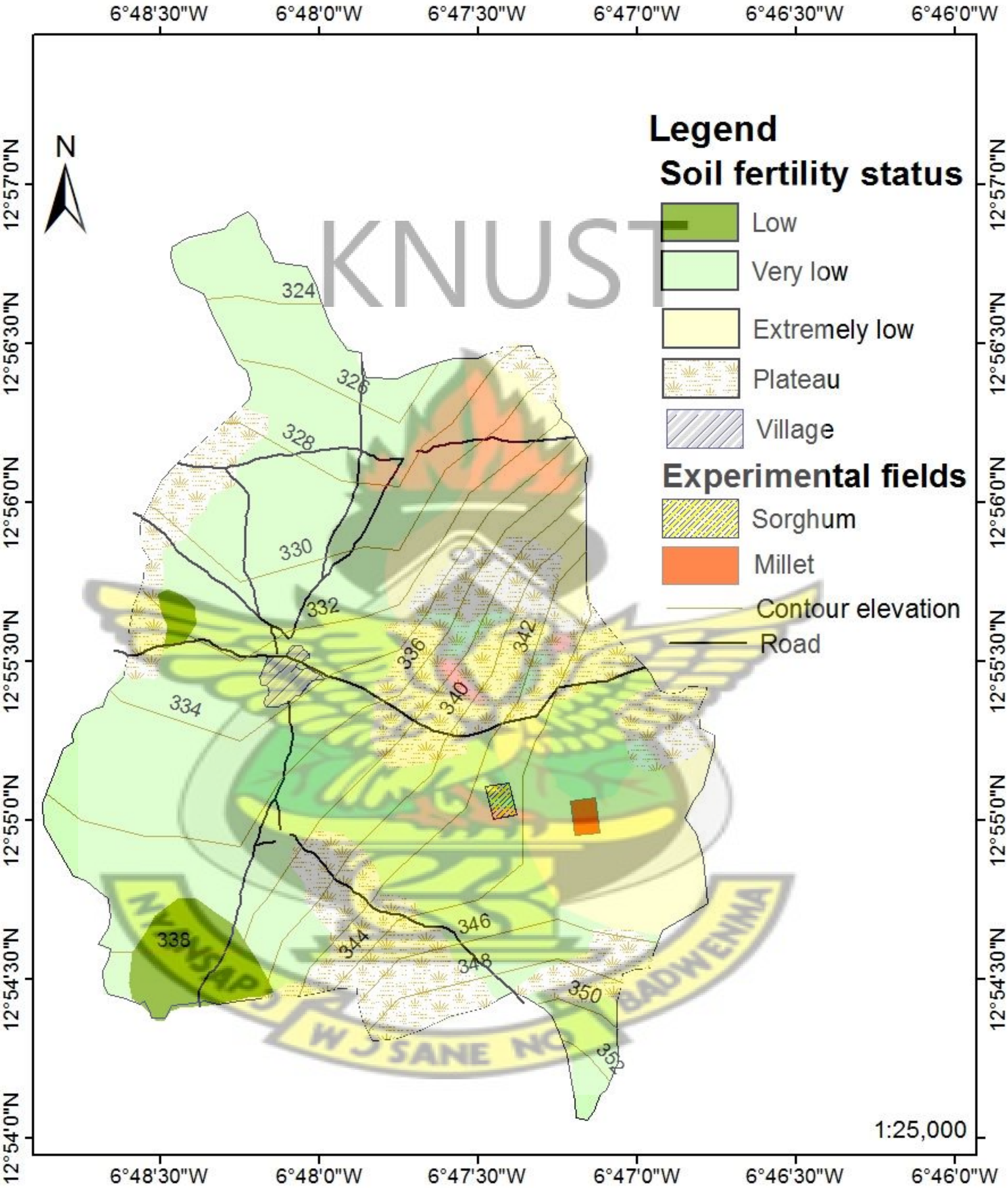

Figure 4.21: Soil fertility status at Siguidolo in 2013

4.2.2.8 Fertilizer usage and spatial distribution in 2013

The types, composition and rates of mineral fertilizers used in the study area are presented in Table 4.5 showing the specific crops for which they are recommended. The spatial distribution of the fertilizers in 2013 is presented in Figure 4.22. Table 4.6 shows the areal coverage of the fertilizers. Organic fertilizers and intergrated organic and mineral fertilizers occupied the greatest area of 333.51 ha. About 24.1% of the area received no fertilizer. The extremely low fertility areas tended to receive more nutrient application. Indications are that, even in those areas where fertilizers were applied, the right quantities were seldom used.

Table 4.5: Fertilizers used at Siguidolo in 2013

Type of fertilizer	Crop	Composition%					Rates Kg^{-1}
		N	P_2O_5	K_2O	S	B	
Complex cotton	Cotton	14	18	18	6	1	
		14	22	12	7	1	150 to 200
		22	13	12	7	1	
Complex Cereal	Maize, Millet, Sorghum	15	15	15	-	-	100
Urea	Cotton	46	-	-	-	-	50
	Cereals						100 to 150
Diammonium phosphate	Rice	18	46	-	-	-	100
	Sugar cane						200 to 300

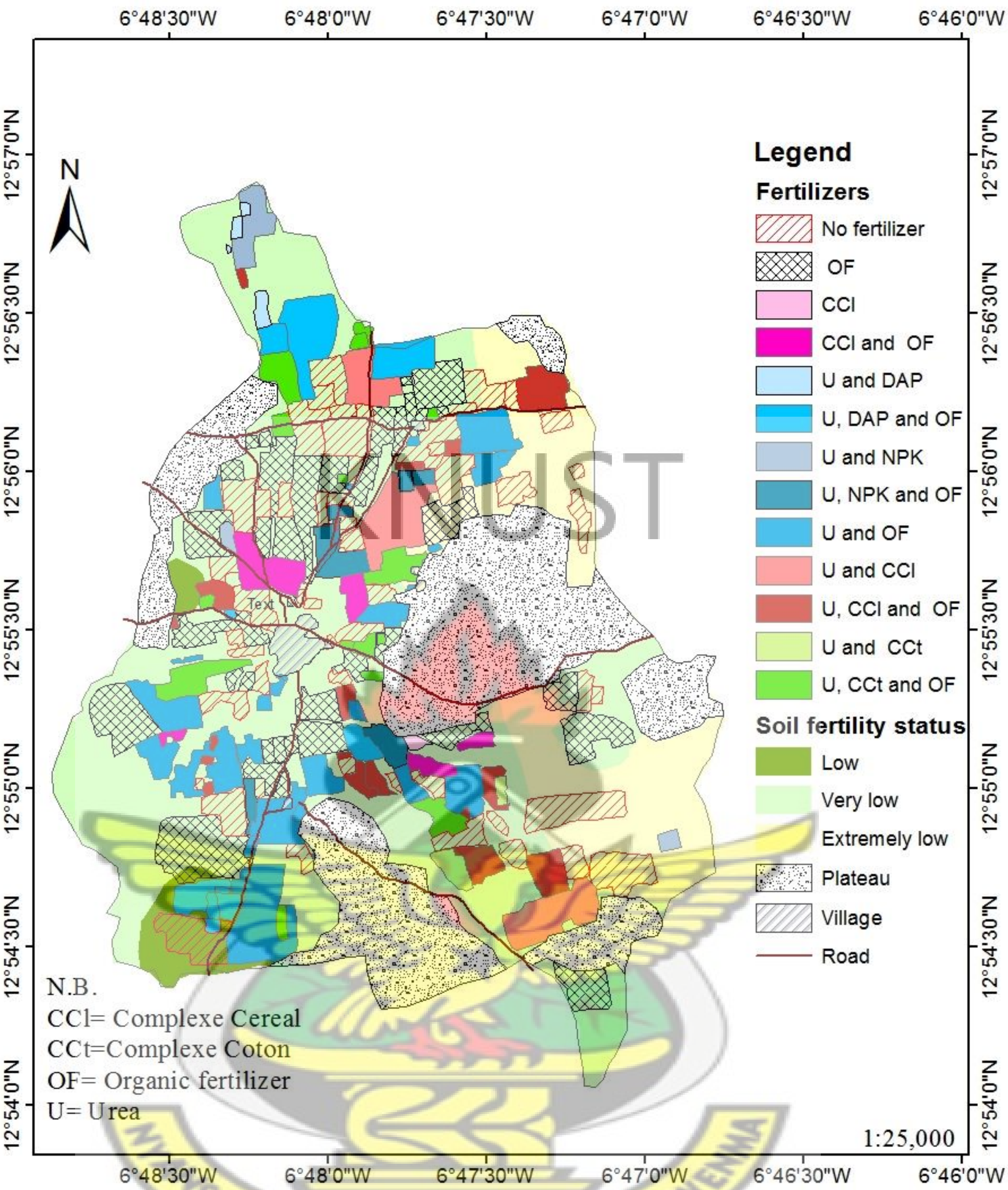

Figure 4.22: Spatial distribution of fertilizers used at Siguidolo in 2013

Table 4.6: Areas covered by fertilizers in 2013

Fertilizers	Area (ha)	Area (%)
no fertilizer	122	24.11
Organic fertilizer	132.01	26.08
Mineral fertilizer	50.2	9.90
Organic and mineral fertilizer	201.5	39.93
Total	506	100%

4.2.2.9. Sorghum and millet yield

Information on soil fertility status, spatial distribution of millet and sorghum grain yields is presented in Figures 4.23 and 4.24 respectively. The means millet grain yield in the study area are 414.66 kg ha^{-1} on soil with low nutrient status, 703.80 kg ha^{-1} on soil with very low nutrient status and 558.2 kg ha^{-1} on soil with extremely low nutrient status. The corresponding yields for sorghum are 445 kg ha^{-1}, 448.04 kg ha^{-1} and 404.12 kg ha^{-1} . The very low and extremely low nutrient status soils were compensated for by greater amounts of fertilizer application with a consequent higher grain yield than the relatively better low fertility soils. The percentage area of the low, very low and extremely low fertility status soils that received fertilizers were 44.4, 80.33 and 71.01 respectively (Table 4.7).

Table 4.7: Soil amendments applied in 2013 and percentage area of coverage

Soil amendments	**Soil fertility status**		
	Low	**Very low**	**Extremely low**
	--------------% area covered-----------------		
No fertilizer	55.57	19.67	28.96
Organic fertilizer	15.82	23.69	40.76
Mineral fertilizer	-	12.87	1.99
Organic and mineral fertilizer	28.61	43.77	28.29
Total	100	100	100

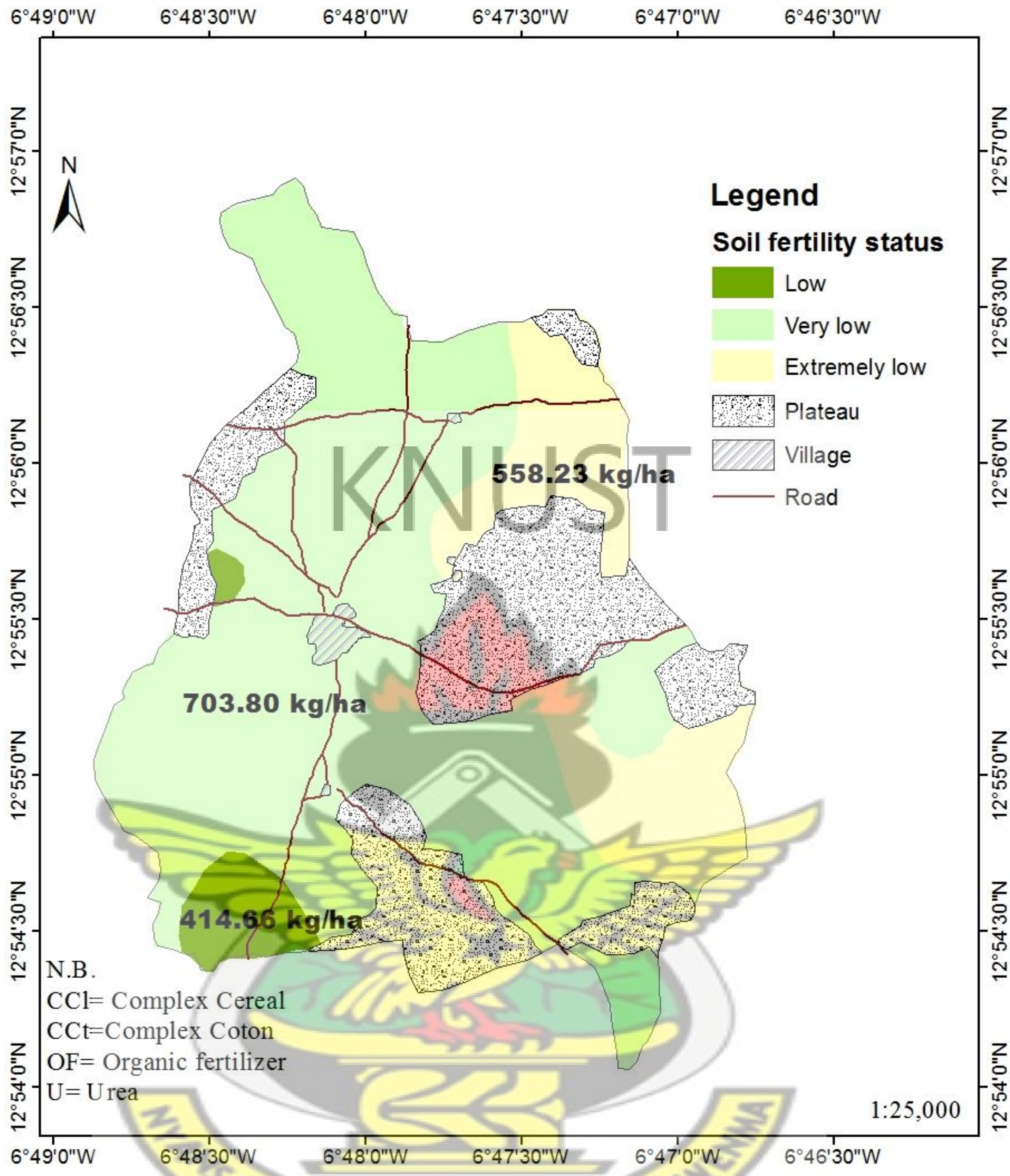

Figure 4.23: Spatial distribution of soil fertility status and millet grain yield in 2013

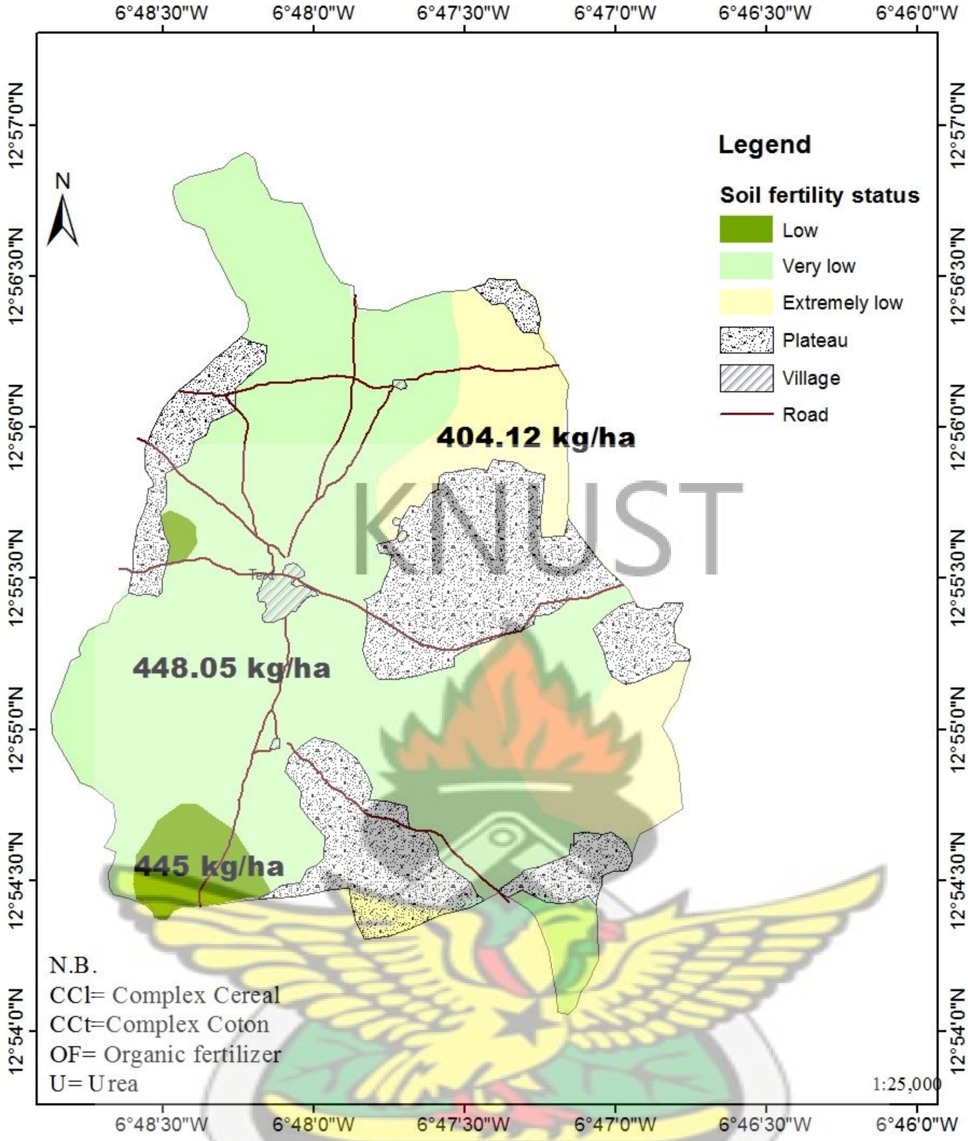

Figure 4.24: Spatial distribution of soil fertility status and sorghum grain yield in 2013

4.3. Impact of tillage and soil amendments on selected chemical properties and the yield of millet and sorghum

To facilitate reading, the treatments studied are presented below: The treatments involved the following tillage and soil amendments

- **Tillage:**
  - Ridge tillage (R_1)
  - Hoe tillage (R_2)
- **Amendments :**

  P_0=No amendment,

  P_1= Profeba

  P_2= Profeba + urea

  P_3= Profeba + Tilemsi phosphate+ urea

  P_4=Profeba + lime+ urea

4.3.1 Initial physical-chemical properties of the soil before start experiment

The experimental soil was characterized before the experiments by its physical and chemical properties. The results (Table 4.9) showed the soil to be sandy loam. This soil type occupied 78% of the entire study area. The pH was strongly acidic, implying the need for liming. The soil organic carbon and all the nutrients were very low. Sustaining crop production on the soil would require substantial application of mineral/organic fertilizers.

Table 4.8*:* Initial physical and chemical properties of experimentation fields

Soil parameters	Levels
pH(1:1, H_2O)	4.78
Organic Carbon (%)	0.45
Total N (%)	0.02
Available P (mg kg^{-1})	2.04
Exchangeable K ($cmol_c$ kg^{-1})	0.10
Exchangeable Ca ($cmol_c$ kg^{-1})	1.54
Exchangeable Mg ($cmol_c$ kg^{-1})	0.81
Exchangeable Na ($cmol_c$ kg^{-1})	0.06
ECEC ($cmol_c$ kg^{-1})	2.57
Sand (%)	77.02
Silt (%)	19.34
Clay (%)	3.63

4.3.2 Initial chemical characteristics of Profeba compost

The chemical characteristics of the Profeba compost used in the experiment are presented in Table 4.10. The organic carbon content was high with a substantial amount of N that could benefit the soil. C/N ratio was below the recommended level. Exchangeable K and Mg were high. The micronutrient content: Fe, Zn and Cu were also high. However, P and Ca were below the recommended level. These nutrients content indicated a useful material.

Table 4.9: Chemical analysis of Profeba

Nutrients	Nutrient content
Dry matter content (kg)	51.00
Total N (%)	1.73
Total P (%)	0.40
Total K (%)	1.05
Carbon (%)	47.73
C/N	27.59
Calcium (%)	0.04
Magnesium (%)	0.29
Fe (mg kg^{-1})	120.47
Zn (mg kg^{-1})	46.90
Cu (mg kg^{-1})	2.44

4.3.3 Impact of tillage and soil amendments on soil chemical properties

4.3.3.1. Impact of tillage and soil amendments on pH

Over the two cropping seasons, soil pH was significantly ($p<0.05$) affected by tillage only under sorghum in 2013 (Table 4.11). The highest level of soil pH was observed under ridge tillage.

Soil amendment had no significant ($p>0.05$) effect on soil pH under both sorghum and millet in 2013. However in 2014 soil amendments significantly ($p<0.05$) influenced soil pH under both millet and sorghum.

Soil pH under millet decreased as $P_4 > P_3 > P_2 > P_1 > P_0$ with a range of 4.80 to 5.56 whilst the differences in pH for the P_4, P_3 and P_2 were not significant, they were significantly higher than P_1 and P_0. P_0 also recorded significantly ($P<0.05$) lower pH than P_1. A similar trend was observed under sorghum with pH ranging from 5.58 to

4.36 under P_4 and P_0 respectively. The interaction between soil amendment and tillage practices on pH was significant (P<0.05) under millet in 2013.

Table 4.10: Effect of tillage and soil amendments on soil pH

Soil amendment	**pH(1:1, H_2O)**			
	2013		2014	
	Millet	**Sorghum**	**Millet**	**Sorghum**
P_0	4.93	4.83	4.80	4.36
P_1	4.87	4.90	5.33	5.20
P_2	5.07	5.00	5.48	5.53
P_3	5.02	5.03	5.54	5.45
P_4	4.92	4.95	5.56	5.58
Fpr. (soil amendment)	0.68	0.92	<.001	<.001
Lsd (0.05)	0.32	0.50	0.20	0.29
Tillage practices				
R_1	4.96	5.05	5.44	5.33
R_2	4.96	4.76	5.24	5.15
Fpr. (Tillage practice)	0.98	0.01	0.16	0.15
Lsd (0.05)	0.27	0.45	0.32	0.26
Fpr. (soil amendment x Tillage)	0.02	0.13	0.14	0.13
CV%	5.3	8.3	3.1	4.6

N.B. TPR = Tilemsi Phosphate Rock

Table 4.11: Mean values of tillage x amendments interaction on pH under millet (2013)

Soil amendment	Tillage	
	R_1	R_2
P_0	4.77	5.09
P_1	5.01	4.73
P_2	5.09	5.04
P_3	5.26	4.78
P_4	4.67	5.17
Lsd(0.05)	0.4504	
CV (%)	5.3	

R_1 = Ridge tillage, R_2 = Hoe tillage

Table 4.11: shows the tillage x amendments interaction means. The highest pH was recorded under P_3 x R_1 with P_4 x R_1 recording the least pH. Whereas the main effects of amendment were not significant, the impact of P_3 was enhanced under R_1 to significantly ($P<0.05$) record higher pH than P_0R_1 and P_4R_1. On the other hand, whilst the effect of tillage on pH was not significant, their impact became significantly ($P<0.05$) different under the various soil amendments with P_4R_2 and P_3R_1 recording higher pH than P_4R_1 and P_3R_2 respectively. The impact of amendments and tillage on pH therefore depended on the level of each other.

4.3.3.2 Impact of tillage and soil amendments on soil organic carbon

The effect of tillage practices on soil organic carbon was not significant ($p>0.05$) under both millet and sorghum in both 2013 and 2014. The greater soil organic carbon was observed under ridge tillage on both millet and sorghum fields (Table 4.12).

Soil amendments did not have any significant difference on soil organic carbon content in 2013. However in 2014, significant ($p<0.05$) differences were observed between soil amendments.

Soil organic carbon under millet in 2014 ranged between 0.37 and 0.54. Significant differences were observed between P_0 and P_1, P_0 and P_1 and P_2, P_3 and P_4. In 2014, SOC differed significantly between P_0 and all amendments and P_3 and P_2. All other differences were not significant. The values ranged from 0.33 to 0.53 with a trend of $P_4 > P_3 > P_1 > P_2 > P_0$. The interaction between soil amendments and tillage was not significant.

Table 4.12: Effect of tillage and soil amendments on soil organic carbon content

Soil amendment	Carbon (%)			
	2013		2014	
	Millet	**Sorghum**	**Millet**	**Sorghum**
P_0	0.38	0.32	0.37	0.33
P_1	0.32	0.39	0.50	0.49
P_2	0.37	0.41	0.53	0.48
P_3	0.37	0.31	0.54	0.51
P_4	0.36	0.35	0.54	0.53
Fpr. (soil amendment)	0.38	0.17	0.003	<.001
Lsd (0.05)	0.06	0.09	0.03	0.05
Tillage practices				
R1	0.36	0.38	0.52	0.49
R2	0.35	0.33	0.51	0.45
Fpr. (Tillage practice)	0.73	0.11	0.44	0.14
Lsd (0.05)	0.07	0.06	0.03	0.06
Fpr. (soil amendment x Tillage)	0.32	0.87	0.69	0.28
CV%	14.4	21.6	6.2	7.7

4.3.3.3 Effect of tillage and soil amendments on soil nitrogen, phosphorus and Potassium

Tillage practices significantly ($p<0.05$) affected soil nitrogen under sorghum in 2013 (Table 4.13). But, the effect was not significant under millet. In 2014, tillage practices had no significant effect under sorghum but the differences under millet were significant. However greater soil nitrogen was recorded under ridge tillage on both millet and sorghum fields in 2013 and 2014.

In 2013 soil amendments showed significant ($p<0.05$) effect on total nitrogen under millet but the effect was not significant ($p>0.05$) under sorghum. In 2014, significant

($p<0.05$) effect was found between soil amendments under both millet and sorghum. The values of N were however low ranging from 0.01 to 0.03.

The interaction between tillage practices and soil amendment was not significant under both millet and sorghum in both 2013 and 2014.

Table 4.13: Effect of soil amendments on total nitrogen content

Soil amendment	**Total Nitrogen (%)**			
	2013		2014	
	Millet	**Sorghum**	**Millet**	**Sorghum**
P_0	0.01	0.03	0.01	0.01
P_1	0.01	0.03	0.01	0.02
P_2	0.02	0.03	0.02	0.03
P_3	0.02	0.03	0.02	0.02
P_4	0.02	0.03	0.02	0.03
Fpr. (soil amendment)	0.02	1.00	0.01	<.001
Lsd (0.05)	0.007	0.013	0.0071	0.009
Tillage practices				
R_1	0.01	0.03	0.019	0.02
R_2	0.01	0.02	0.016	0.02
Fpr. (Tillage practice)	0.37	0.01	0.06	0.25
Lsd (0.05)	0.012	0.010	0.003	0.004
Fpr. (soil amendment x Tillage)	0.34	0.44	0.90	0.98
CV%	39.5	35.6	33.1	29.8

The effect of soil amendment on available P is presented in Table 4.14. Tillage practices did not significantly ($p>0.05$) affect soil phosphorus under millet 2013. On the other hand the effect was significant ($p<0.05$) under sorghum. In 2014, tillage practices had significant effect on P under millet but not under sorghum. Ridge tillage recorded higher available P under both millet and sorghum in 2013 and 2014.

Soil amendments showed significant (p>0.05) effect on soil phosphorus under both millet and sorghum in 2013 and 2014.

In 2013 available P under millet ranged from 1.20 to 1.91 mg kg^{-1} in the order of P4 > P_1 > P_2 =P_2 > P_0 (Table 4.13). Only P_0 had significantly (P<0.05) less available P than the rest of the amendments which did not differ (P<0.05). In the case of sorghum the impact of soil amendments on P ranked as P_1 > P_0 > P_4 > P_2 > P_3 with a range of 1.04 to 2.16 mg kg^{-1}. The latter three amendments, which did not differ significantly, recorded lower available P (P<0.05) than P_1 and P_0 which differed significantly. P_1 and P_2 recorded the highest and lowest P respectively.

In 2014 the soil amendments differed significantly in their effect on P. P under millet was between1.39 and 2.47 mg kg^{-1} in a decreasing order of P_3 > P_4 > P_1 > P_2 > P_0. P3 and P4 and P1 and P2 did not differ significantly. The former two amendments had significantly higher P than the remaining amendments with P_0 recording the least P. Available P under sorghum was higher than that of 2013 with values varying from 1.65 to 4.01 mg kg^{-1} and decreasing as P_3>P_4>P_2>P_1>P_0. In all cases, the differences were significant (P<0.05)

Table 4.14: Effect of soil amendments on available phosphorus

Soil amendments	Available Phosphorus mg kg^{-1}			
	2013		2014	
	Millet	Sorghum	Millet	Sorghum
P_0	1.20	1.25	1.39	1.65
P_1	1.56	2.16	2.08	2.45
P_2	1.50	1.21	2.45	3.24
P_3	1.50	1.04	2.47	4.01
P_4	1.91	1.22	2.45	3.53
Fpr. (soil amendment)	0.04	<.001	<.001	<.001
Lsd (0.05)	0.42	0.27	0.24	0.47
Tillage practices				
R_1	1.56	1.24	2.06	3.27
R_2	0.10	1.11	1.88	2.69
Fpr(Tillage practice)	0.78	0.04	0.051	0.11
Lsd (0.05)	0.89	0.11	0.02	0.80
Fpr(soil amendment x Tillage)	0.77	0.51	0.67	0.04
CV%	22.6	18.9	10.3	13.0

Table 4.15: Mean values of tillage x amendments interaction on available P under sorghum (2014)

Soil amendment	Tillage	
	R_1	R_2
	mg kg^{-1}	
P_0	1.59	1.72
P_1	2.16	2.75
P_2	3.28	3.21
P_3	3.44	4.59
P_4	2.98	4.08
Lsd (0.05)	0.8774	
CV (%)	8.3	

R_1 = Ridge tillage, R_2 = Hoe tillage

The impact of tillage x soil amendments interaction on available P was significant (P<0.05) under sorghum in 2014. Table 4.15: indicates the mean values. P_2 x R_1 and P_3 x R_1 significantly (P<0.05) recorded higher available P than the remaining soil amendments x tillage interactions under sorghum, which did not differ significantly P_3 x R_2 and P_4 x R_2 recorded significantly higher P than all the remaining interaction forms. P_0R_2 had the least P

The mean exchangeable K content of the soil under the soil amendments and tillage is presented in Table 4.16. Tillage practices did not significantly (p>0.05) affect soil potassium content under millet in 2013 but the effect was significant (p>0.05) under sorghum. In 2014 the impact of tillage on potassium content under both millet and sorghum was not significantly (p<0.05) different. The ridge tillage recorded higher K under millet and sorghum fields in both 2013 and 2014.

No significant effect was observed between soil amendments and soil potassium content under both millet and sorghum in both 2013 and 2014.

The highest potassium was observed under P_3 under millet in 2013 and under sorghum in 2014.

Table 4.16: Effect of soil amendments on exchangeable potassium content

Soil amendment	**Exchangeable Potassium cmol$_c$ kg^{-1}**			
	2013		2014	
	Millet	**Sorghum**	**Millet**	**Sorghum**
P_0	0.16	0.10	0.04	0.021
P_1	0.16	0.13	0.05	0.023
P_2	0.17	0.13	0.05	0.021
P_3	0.182	0.15	0.05	0.026
P_4	0.180	0.13	0.04	0.025
Fpr. (soil amendment)	0.96	0.39	0.45	0.76
Lsd (0.05)	0.07	0.04	0.011	0.009
Tillage practices				
R_1	0.18	0.14	0.05	0.026
R_2	0.15	0.11	0.04	0.020
Fpr. (Tillage practice)	0.29	0.04	0.13	0.18
Lsd (0.05)	0.04	0.02	0.007	0.010
Fpr. (soil amendment x Tillage)	0.43	0.60	0.45	0.76
CV%	38.3	30.5	20.6	33.0

4.3.4. Effect of Tillage and soil amendments on yields

4.3.4.1 Effect of Tillage and soil amendments on millet and sorghum grain yield

The impact of tillage and soil amendments on crop yield is presented in Table 4.18. Millet grain yield under the tillage practices differed significantly ($P<0.05$) in 2013 and 2014. The differences in sorghum grain yield were however not significant in both seasons. The ridge tillage recorded higher grain yield in both millet and sorghum.

Soil amendments, on the other hand significantly ($P<0.05$) affected the yield of millet and sorghum in 2013 and 2014.

In 2013, millet yield ranged from 311 to 1321 kg ha^{-1} with a decreasing trend of $P_4 > P_2 > P_3 > P_1 > P_0$. Apart from P_2 and P_3, which did not differ significantly, all the other differences were significant ($P<0.05$). In 2014 millet yield, ranging between 384 and 1251 kg ha^{-1} was highest, and ranked as $P_3 > P_2 > P_4 > P_1 > P_0$. Whilst the differences in yield under the first three amendments were not significant, their yields were significantly ($P<0.05$) higher than P_1 and P_0 which also differed significantly.

In 2013, the grain yield of sorghum decreased as $P_2 > P_1 > P_4 > P_3 > P_0$ with a range of 55 to 375 kg ha^{-1}. The differences between the treatments were significant, except those between P_2 and P_1 and P_4 and P_3. Sorghum yield, like the millet, did not follow any consistent trend in the two seasons.

In 2014, sorghum grain yield, which was higher than that of 2013, varied from 101 to 1309 kg ha^{-1} with an increasing trend of $P_0 < P_1 < P_3 < P_2 < P_4$. Apart from P_4 and P_2 which did not differ significantly, the grain yield differed significantly among the treatments.

In all cases, the control recorded the least yield. The highest grain yield, however, did not follow any consistent trend.

Table 4.17: Effect of Tillage and soil amendments on sorghum and millet grain yield

Soil amendment	**Grain yield kg ha^{-1}**			
	2013		2014	
	Millet	**Sorghum**	**Millet**	**Sorghum**
P_0	311	55	384	101
P_1	660	372	1014	1036
P_2	932	375	1235	1261
P_3	894	199	1251	1222
P_4	1321	206	1223	1309
Fpr. (soil amendment)	<001	<001	<001	<001
Lsd (0.05)	281.7	99.1	88.8	84.5
Tillage practices				
R_1	870	281	1056	1011
R_2	777	202	986	960
Fpr. (Tillage practice)	0.63	0.006	0.01	0.07
Lsd (0.05)	723	25.7	42	58.8
Fpr. (soil amendments x Tillage)	0.11	0.04	0.13	0.46
CV%	27.9	33.5	7.1	7.0

Table 4.18: Mean of tillage x amendments interaction on sorghum grain yield in 2013

Soil amendments	**Tillage**	
	R_1	**R_2**
	kg ha^{-1}	
P_0	58	52
P_1	415	329
P_2	509	241
P_3	239	160
P_4	186	227
Lsd(0.05)	131.6	
CV (%)	33.5	

R_1= Ridge tillage; R_2= Hoe tillage

Table 4.18: shows tillage x soil amendments interaction means on sorghum grain yield in 2013. The higher grains were observed under P_2 with 509 kg ha^{-1} and P_1 with 329 kg ha^{-1} and R_1 and R_2 respectively. The P x R_1 interaction showed P_0R_1 to record the least whilst P_2 R_1 had the highest yield of sorghum. The differences between P_1R_1, P_2R_1 were not significant. In the case of P x P_2 interaction P_0R_2 and P_1R_2 recorded the least and highest yields respectively.

4.3.4.2. Effect of tillage and soil amendments on biomass yield in 2014

The mean biomass under tillage and soil amendments is presented in Table 4.19. Biomass yield was significantly ($P<0.05$) affected by tillage and soil amendments. The ridge tillage recorded significantly higher sorghum and millet biomass yield than the hoe tillage.

The mean biomass yield of millet ranged from 998 to 6637 kg ha^{-1} under soil amendments in the order of $P_3 > P_4 > P_2 > P_1 > P_0$. The differences among the treatments, except that between P3 and P4 were significant ($P<0.05$)

The biomass yield of sorghum among the soil amendments treatments varied from 1424 to 6983 kg ha^{-1}. The mean yield was in a decreasing order of $P_4 > P_1 > P_3 > P_2 > P_0$ with significant ($P<0.05$) differences among the treatments except P2 and P3.

Table 4.19: Effect of tillage practice and soil amendments on biomass in 2014

Soil amendment	Biomass kg ha^{-1}	
	Millet	Sorghum
P_0	998	1424
P_1	3982	5740
P_2	5564	4827
P_3	6637	4924
P_4	6030	6983
Fpr. (soil amendment)	<.001	<.001
Lsd (0.05)	561.8	700.4
Tillage practices		
R_1	4817	5695
R2	4468	3864
Fpr. (Tillage practice)	0.01	<.001
Lsd (0.05)	254.3	442.9
Fpr. (soil amendment x Tillage)	0.06	<.001
CV%	9.9	12.2

Table 4.20: Mean of tillage x amendments interaction on sorghum biomass yield in 2013

Soil amendments	Tillage	
	R_1	R_2
	kg ha^{-1}	
P_0	1609.	1238
P_1	7284	4196
P_2	6818	2836
P_3	5478	4371
P_4	7284	6682
Lsd(0.05)	990.5	
CV (%)	12.2	

R_1= Ridge tillage; R_2= Hoe tillage

Table 4.20: shows tillage x soil amendments interaction means on sorghum biomass yield in 2013. The higher biomass was observed under P_1 and P_4 with 7284 kg ha^{-1} under ridge tillage and P_4 with 6682 kg ha^{-1} under hoe tillage. The P x R_1 interaction showed P_0R_2 to record the least whilst P_1 R_1 and P_4R_1 had the highest biomass of sorghum.

4.3.4.3. Relationship between some soil factors and grain yield

Correlation analysis was done to measure the strength of the linear relationship that exists between the selected soil parameters and grain yield while regression was used to provide expression of grain yield as a function of parameters which were significant.

The correlation coefficients with their significance levels are presented in Table 4.21. Soil pH, Carbon, Total Nitrogen, Available Phosphorus and Exchangeable Potassium were positively and strongly correlated with both sorghum and millet grain yield in 2013 and 2014. The exceptions were the correlation between K and millet in 2014 which was not significant and the negative correlation between K and Sorghum in 2014.

Table 4.21: Correlation between crop grain yield and the selected soil nutrients

	Grain yield			
Soil factors	**2013**		**2014**	
	Millet	**Sorghum**	**Millet**	**Sorghum**
pH	0.54**	0.60**	0.85**	0.74**
OC	0.47*	0.73**	0.71**	0.41*
N	0.70**	0.64**	0.75**	0.64**
Avail P	0.84**	0.55*	0.76**	0.68**
Exch K	0.57*	0.47*	0.16 Ns	-0.52*

Ns = not significant; ** =Significant at P<0.01; * =Significant at P<0.05

Regression between some selected soil parameter and millet yield

The regression equations are presented in Figures 4.28 to 4.35 for millet. Apart from the relationship between millet grain yield and pH in 2013 and carbon in 2013 which recorded very low R^2 values, the R^2 of the remaining relationships was satisfactory for predictive purposes with a range of 0.49 to 0.71.

In the case of sorghum (Figure 4.36 to 4.43) low R^2 values were recorded for the relationship between grain yield and pH in 2013, % N in 2013 and available P in 2013. The remaining R^2 values ranged from 0.53 to 0.84 which were considered satisfactory for prediction.

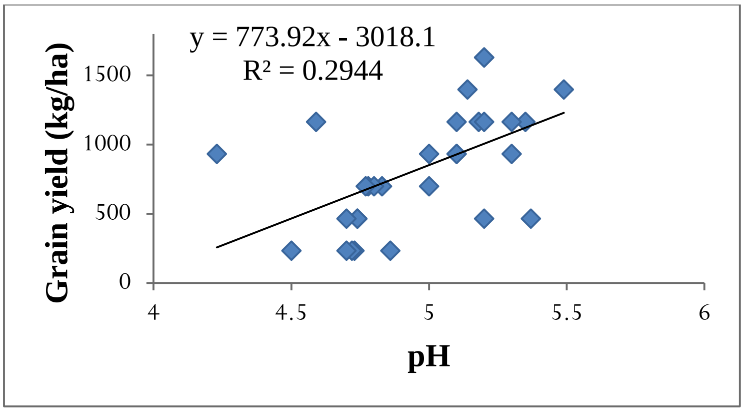

Figure 4.28: Relationship between soil pH and millet grain yield in 2013

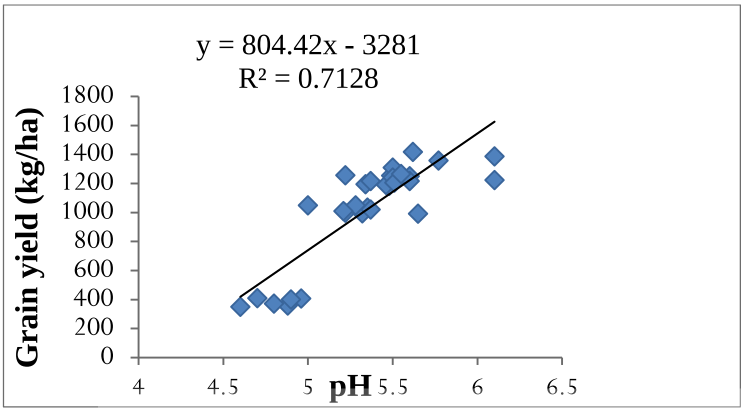

Figure 4.29: Relationship between soil pH and millet yield in 2014

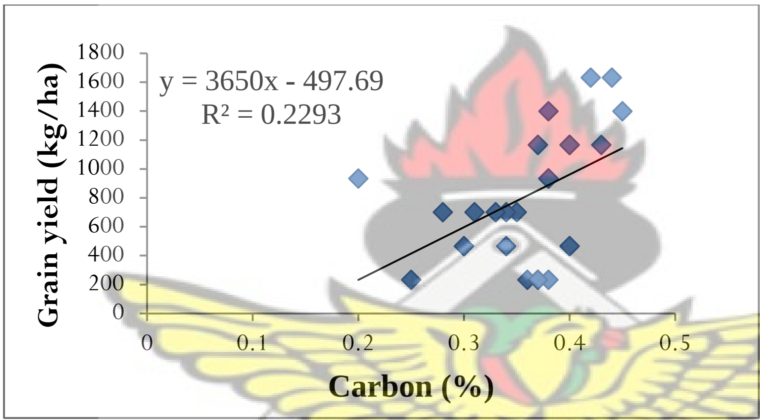

Figure 4.30: Relationship between soil carbon and millet yield in 2013

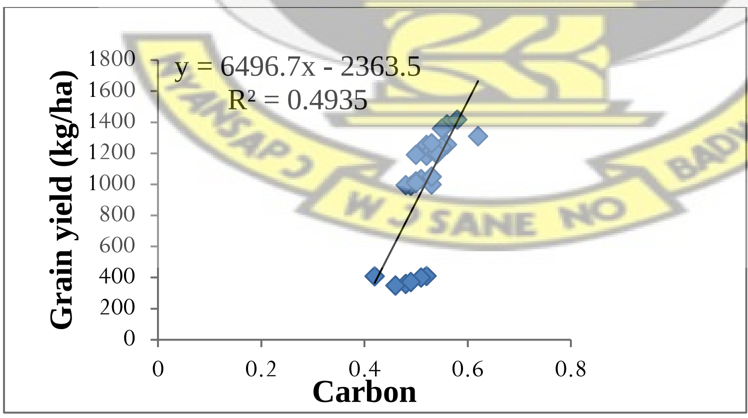

Figure 4.31: Relationship between soil carbon and millet grain yield in 2014

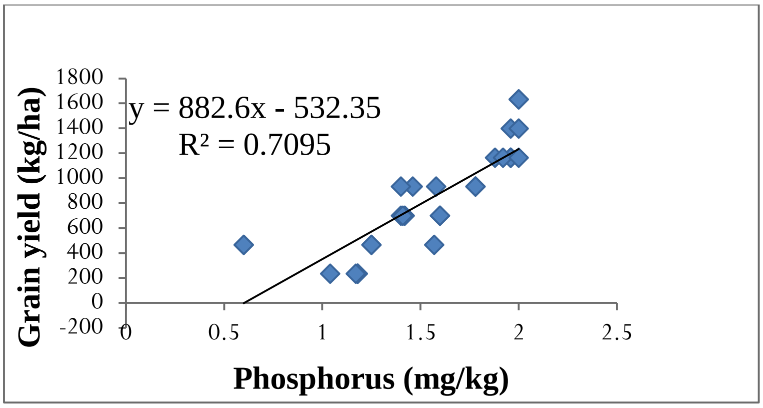

Figure 4.32: Relationship between soil phosphorus and millet yield in 2013

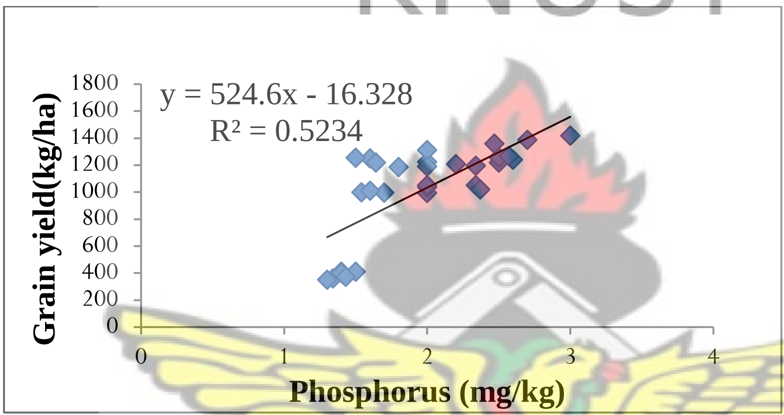

Figure 4.33: Relationship between soil phosphorus and millet yield in 2014

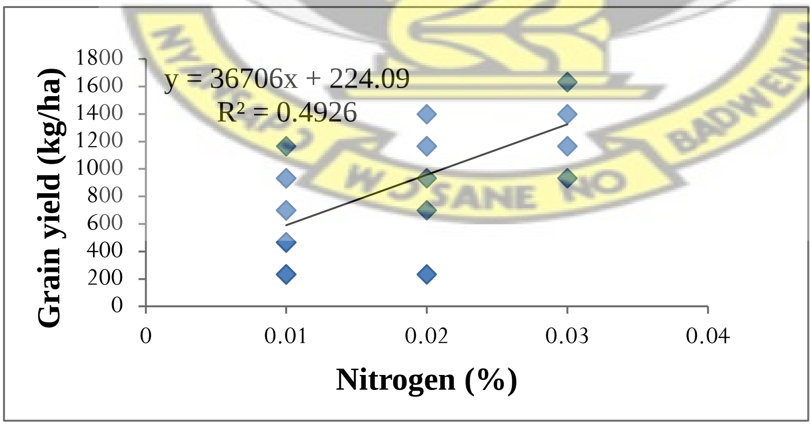

Figure 4.34: Relationship between soil nitrogen and millet yield in 2013

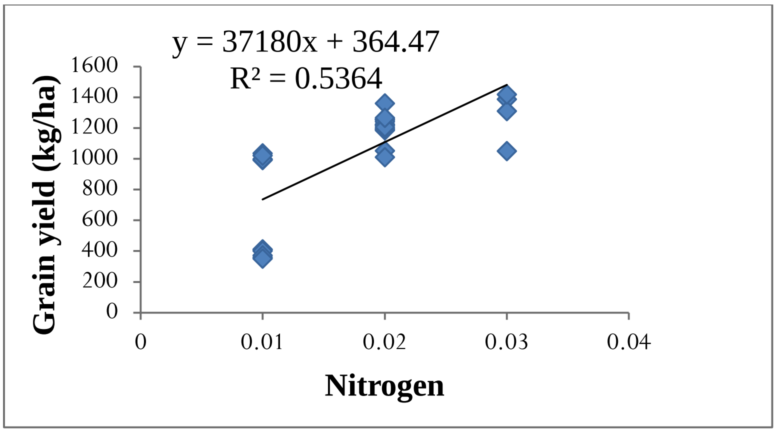

Figure 4.35: Relationship between soil nitrogen and millet yield in 2014

Regression analysis between some selected parameter and sorghum grain yield

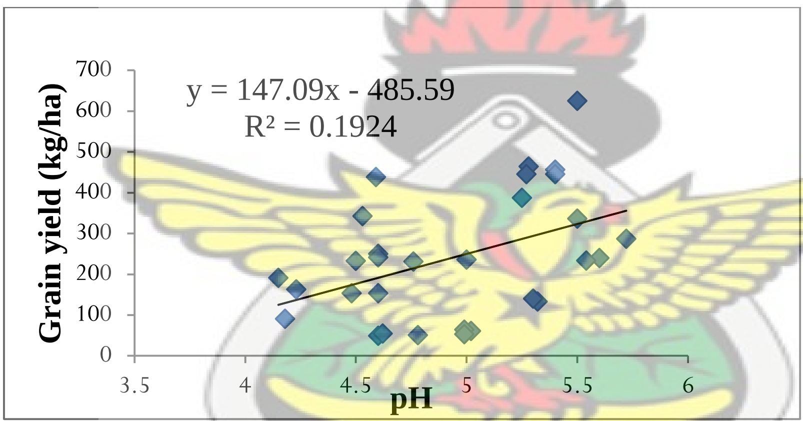

Figure 4.36: Relationship between soil pH and sorghum grain yield in 2013

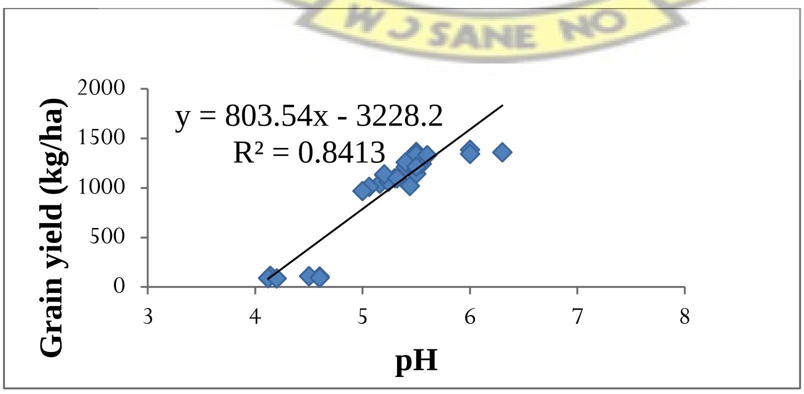

Figure 4.37: Relationship between soil pH and sorghum grain yield in 2014

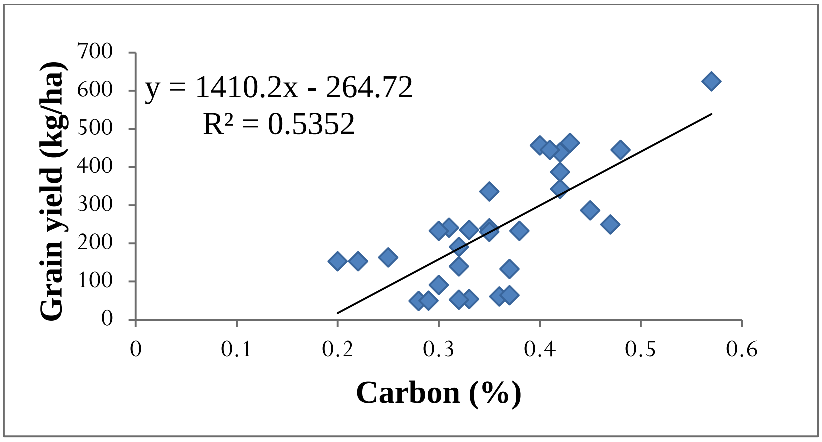

Figure 4.38: Relationship between soil carbon and sorghum grain yield in 2013

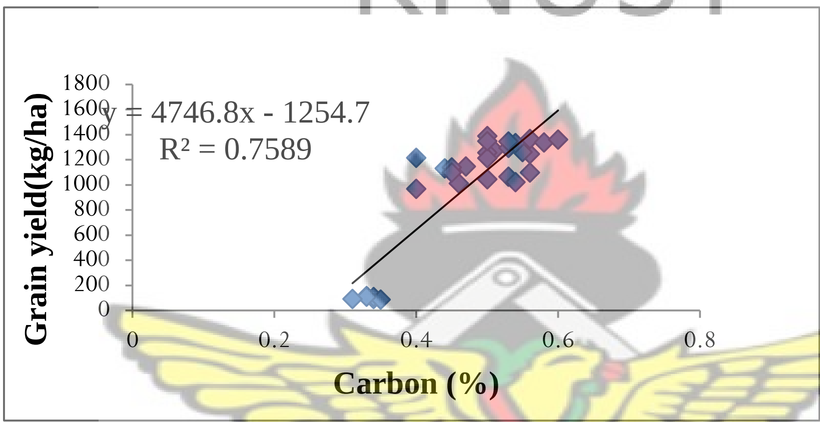

Figure 4.39: Relationship between soil carbon and sorghum grain yield in 2014

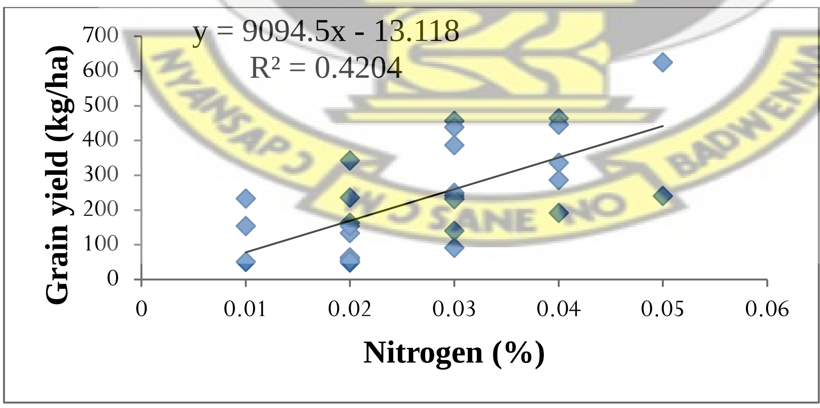

Figure 4.40: Relationship between soil nitrogen and sorghum grain yield in 2013

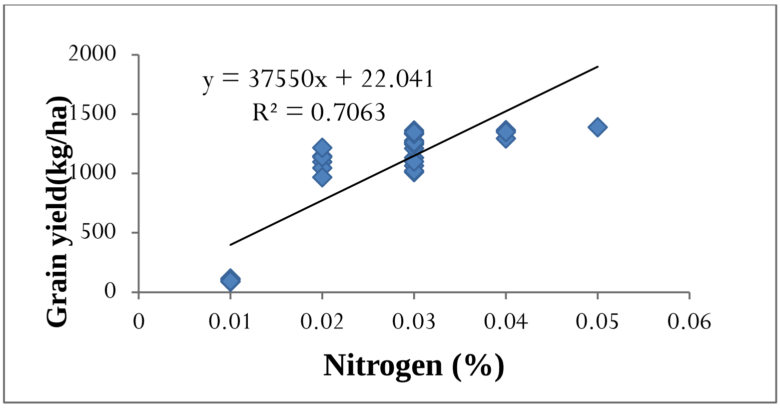

Figure 4.41: Relationship between soil nitrogen and sorghum grain yield in 2014

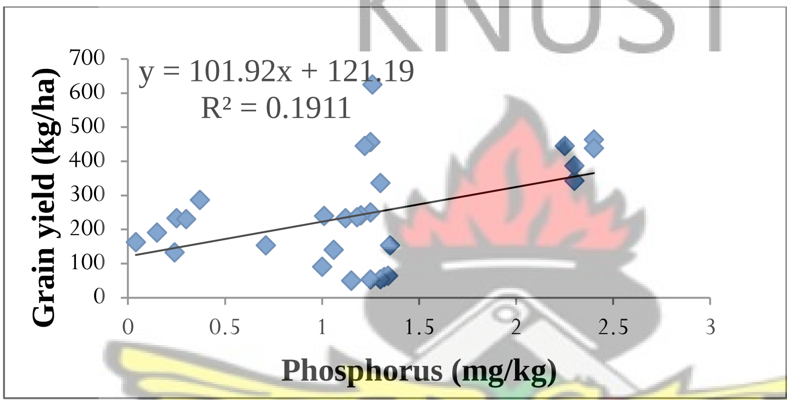

Figure 4.42: Relationship between soil nitrogen and sorghum grain yield in 2013

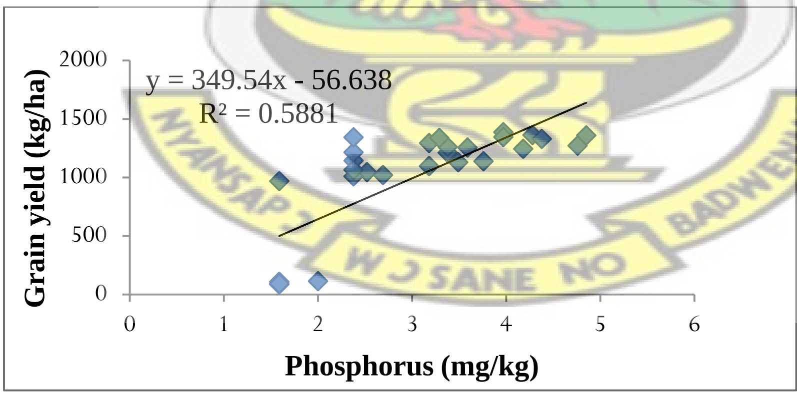

Figure 4.43: Relationship between soil nitrogen and sorghum grain yield in 2014

4.4. Profitability of soil amendment options and tillage practices

4.4.1 Effect of tillage practice and soil amendments on Millet value cost

Table 4.22 shows the VCR of millet in 2014. On millet field, with ridge tillage, the overall trend from the highest to the lowest VCR was Profeba + urea > Profeba + urea + TPR> Profeba> profeba + Urea + Lime. The corresponding trend for the hoe tillage was Profeba + urea> Profeba + urea + TPR> Profeba> profeba + Urea + Lime. The best VCR was with Profeba + urea under both ridge and hoe tillage and the lowest was obtained under Profeba + Urea + Lime.

Table 4.22: VCR of Millet 2014

Tillage	Soil amendments	Grain yield (kg ha^{-1})	Income from grain (CFA)	Cost of amendments (CFA)	VCR
RT	Control	397.31	-	-	-
RT	Profeba	1026.11	110040	152500	0.72
RT	Profeba + urea	1250.46	149301.3	170000	0.87
RT	Profeba+urea+TPR	1274.53	153513.5	175000	0.85
RT	Profeba+urea+lime	1334.01	163922.5	560000	0.29
HT	Control	370.4	-	-	-
HT	Profeba	1001	110355	152500	0.43
HT	Profeba+ urea	1219.58	148606.5	170000	0.55
HT	Profeba+urea+TPR	1226.38	149796.5	175000	0.54
HT	Profeba+urea+lime	1112.24	129822	560000	0.19

1kg millet=175 CFA

4.4.2 Effect of tillage practice and soil amendments on sorghum value cost ratio

The VCR under sorghum is presented in Table 4.23. The VCR under ridge tillage ranked as Profeba + Urea + TPR> Profeba + Urea> Profeba> Profeba + urea + lime; and Profeba + urea> Profeba> Profeba + urea+ TPR> Profeba + urea + lime under hoe tillage. The application of Profeba + urea had the best VCR under both ridge and hoe tillage. The lowest VCR was found under hoe tillage with the application of Profeba + Urea + Lime.

Table 4.23: VCR of Sorghum 2014

Tillage	Soil amendments	Grain yield (kg ha^{-1})	Income from grain (CFA)	Cost of amendments (CFA)	VCR
RT	Control	110.63	-	-	-
RT	Profeba	1044.3	163388.8	152500	1.07
RT	Profeba+ urea	1290.83	206531.5	170000	1.21
RT	Profeba+urea+TPR	1293.86	207061.8	175000	1.18
RT	Profeba+urea+lime	1317.63	211221.5	560000	0.37
HT	Control	90.74	-	-	
HT	Profeba	1026.88	163824.5	152500	1.07
HT	Profeba+ urea	1232.16	199748.5	170000	1.17
HT	Profeba+urea+TPR	1149.96	185363.5	175000	1.05
HT	Profeba+urea+lime	1301.08	211809.5	560000	0.37

CHAPTER FIVE

5.0 DISCUSSION

The major problem constraining crop production and food security in Mali is the low inherent fertility of the soils and its continued decline over the many years of cultivation by the predominant smallholder farmers. In order to reverse this trend, there is the need to replenish the lost nutrients which results from crop uptake and harvest, erosion and leaching. This will require the development and implementation of spatially-oriented soil fertility management strategies to benefit the many scattered farms of smallholder farms.

The requirements for the development of an effective nutrient management strategy for a given agro-ecology, include among others, the delineation of the soils and their physical and chemical characteristics, types of land degradation; vegetation cover, relief and the dynamics of the cropping system.

The spatial distribution of data on these parameters and their magnitudes facilitate the establishment of the fertility status of the soils in the entire area which in turn, will support what site-specific nutrient management strategy to adopt. This approach is recognized as a better alternative to the current prevailing blanket nutrient application rates often recommended in most sub-Saharan countries. The significance of the approach is explicit in the objectives of the current on-going OFRA (Optimizing fertilizers Recommendations in Africa) project operating in 13 African countries, including Mali (OFRA, 2013).

Among its four objectives is an increased use of spatial information for extrapolation of nutrient response functions and decision tools for optimizing fertilizer use by farmers.

Nevertheless, the past efforts in finding solutions to the soil fertility decline problem in Mali have used the conventional field experimentation approach, the results of which have limited spatial use and applicability for the many dispersed farms and variable bio-physical conditions of the smallholder farmers. Addressing this constraint requires spatially applicable data and solutions which can be obtained by integrating remote sensing and GIS in conventional soil fertility management studies. The lack of such an approach in Mali underscored the use of these tools in this soil fertility management study to support decision making in soil fertility management in Siguidolo as a test case. The resulting spatial database is envisaged to support the dynamic development of nutrient replenishment strategies and cropping trends as well as soil survey under changing farm circumstances over the years. The results are discussed in this section.

5.1 General characteristics of the study area

The processing of the satellite images covering the study site facilitated the delineation and mapping of the relief and topography, vegetation and soil units at the study site.

The areal extent of the study site was 1163 ha with disjointed plateaux located at the north-western, south-eastern and eastern borders and occupying about 23.4% of the total land area. Siguidolo village is located in a depression surrounded by the plateaux.

As an agrarian country, the main land use in the area is agriculture which covers 76% of the study site. Out of this, 57.2% (505.6 ha) was used for crop production in 2013.

The relief map generated, indicated the relief to be generally low with elevation ranging from 300 to 352 m above sea level with the plateaux recording higher values. The slopes range from 1.0 to 4.0 % in steepness.

The delineated rills and gullies indicate that the area is subject to water erosion which accord with the observations made during the ground truthing exercise. During the rainy season, interrill (sheet) erosion is common with intermittent rills and gullies, some of which measure up to 1.0 m deep in the relatively hilly sites. In the depressions and valleys, particularly along the streams, waterlogged conditions often prevail during the rainy season presumably due to high water table.

The coverage of the visual indicators of erosion imply the predominance of rain splash erosion (interrill) over runoff erosion (rills and gullies) which conform with the general erosion characteristics of sites with subdued slopes and sandy soils. The losses of soil and water through erosion have been found to be accompanied by higher concentrations of silt, clay, organic matter and plant nutrients in available forms than the parent soil as reported by several authors (Quansah, 2000; Traore, 2003; Amegashie et al., 2012). This, as similarly reported by Traore (2003) at the study sites, may in part account for the exacerbation of the very low inherent fertility of the arable lands, mostly cultivated intensively to millet and sorghum.

A major factor that affects the magnitude of erosion in any field is the vegetative cover. Thus agronomic or biological measures of soil conservation make use of the role of vegetation in minimizing erosion (Morgan, 2005).

The vegetation provides organic matter with all its beneficial attributes of nutrient cycling, stabilizing soil aggregates, reducing soil erodibility and enhancing nutrient and water holding capacities of the soil. Additionally, the vegetative cover cushions the soil against the erosive forces of water and wind and thereby reduce their detachment and transport capacities with a resultant reduction in erosion (Traore, 2003; Morgan, 2005; Barmani *et al*., 2013).

The effectiveness of vegetative cover in reducing erosion however depends, in part, on its density and spatial coverage, the continuity of the canopy and height (Nanko *et al*., 2008). Mapping the vegetation cover of the study site therefore became necessary. This was done by processing the satellite images and classified using the Normalized Difference Vegetation Index (NDVI).

The three savannah vegetation delineated were essentially in a mosaic. The woodland tended to be concentrated around the stream courses. The bare and grassland with scattered trees appeared to cover the cultivated areas mainly and together, occupied the major part of the study area. The characteristic bare and sparse vegetation predisposed the study site to erosion by water in the rainy season, and wind erosion in dry season, when the little available vegetation is scorched.

The spatial distribution of soils at the site is as important as the vegetation and pertinent to the planning of the site-specific land management and nutrient replenishment strategies. The processing of the satellite images facilitated the identification of 24 soil units developed over sandstone and generally classified as leached ferruginous soils (CPCS, 1967; Dabin et al. 1979). The soil units' map served as the basis for soil sampling for physical and chemical analyses, the quantitative values of which were also mapped.

The maps provide baseline conditions which can be used for monitoring changing trends in soil physical and chemical properties, fertility status, vegetation and cropping systems to facilitate future planning efforts and development of strategies for integrated soil fertility management for sustained improved crop productivity.

The characterization of the soils and their future classification will further facilitate the use of the soil units' map to identify benchmark soils and their extent of coverage for experimentation and extrapolation of results through GIS. This is a prerequisite for, not only reducing the cost of integrated soil fertility management (ISFM) field experimentation but enhancing the coverage and usefulness of the results obtained.

5.2. Cropping system analysis

Information on existing cropping systems in a region, their areal extent, cropping pattern and sequence, and yields, is important for delineating area of the arable land with low to medium crop productivity and which will require integrated soil fertility management for sustaining higher yields.

As demonstrated in this study, the incorporation of GPS data with the GIS technology can play a vital role in cropping system analysis of an area by spatially integrating temporal crop inventory information of the area.

The results showed the soils of the study area to be generally low in fertility. Mineral fertilizers and/or combined mineral and organic fertilizer application are needed to produce any respectable crop yields in the area. However, for convenience of mapping, the area was delineated into low, very low and extremely low fertility. The annual cropping system maps provided the areal extent of the cultivated crops of the area and trends in their area of coverage. The three- year maps also showed trends in cropping patterns and rotations.

The major cropping system was cereal-based either sole or intercrop. These comprised millet and sorghum, which constitute the major staple food of the area, the sole cropping of which tended to decline in 2012 and 2013 relative to their base areal extent in 2011.

From the 2011 baseline, the common rotations in 2012 were sorghum-millet, sorghum –millet/cowpea, sorghum- sorghum/cowpea, millet-sorghum, cotton-maize and cotton- sorghum. The rotation in 2013 relative to 2012 included, sorghum-sorghum, millet/millet-peanut-sorghum/cowpea, sorghum-millet/cowpea, millet-sorghum, sorghum-cotton, cotton-sorghum, maize-cotton and millet-cotton.

The crop rotations and intercrops have significant soil nutrient depletion and uptake implications. In the cereal-cereal rotation, the effective rooting depth of the component crops such as millet, sorghum and maize, which is about 60 cm (Hudson, 1975) is consistently depleted of its nutrients over the years of continuous cereal production with a consequent decline in crop growth and yield. The shift to rotating sole cereal with cereal/legume intercrop ensures the optimization of nutrient usage since the legumes, with effective rooting depth of about 120 cm (Hudson, 1975), utilize the nutrients at this depth in addition to those leached from the 60cm depth for its growth and yield.

Additionally, in the presence of appropriate rhizobia, the legumes fix and enhance the nitrogen stocks of the soils for improved crop growth and yield. Haque *et al*. (1986) reported that by rotating millet/cowpea intercrop with sole millet, grain yield of the latter increased by 100%. Besides, the intercrops present a multi-canopy, structure, for erosion control, as well as minimize parasitic striga infection and provide a risk aversion strategy for food security. Such practices need to be promoted extensively in the Siguidolo area for effective resources use and sustenance of crop production.

Siguidolo is a part of the cotton production zone of Mali. The cultivation of cotton is always accompanied by fertilizer application for optimum production. By rotating cotton with cereals, the latter benefits from the residual fertilizers (mineral and/or organic) used in cotton production. This accounts for the common practice of cotton-cereal-cotton rotation in the study area. Among the cereals, maize is the crop that primarily receives soil amendments. The farmers indicated that maize responds better to fertilizer application than millet or sorghum. However, Kieft *et al*. (1994) noted that the use of organic and mineral fertilizers is very low and that less than 20% of the cultivated areas in Mali are fertilized with mineral fertilizer.

The grain yield of sorghum and millet showed that higher yields were generally recorded on the very low and extremely low fertility soils than the low fertility areas. The delineation of these fertility classes, as indicated in the soil fertility map, pin-pointed the areas that need most attention for nutrient replenishment. The map showing the spatial distribution of fertilizers showed the application of mineral and organic fertilizers to be greater in the very low and extremely low fertility areas. This accounted for the higher yields recorded in these areas than the low fertility areas.

In the light of these observations, farmers in the Siguidolo will benefit from cereal-legume intercrops and rotation and mineral fertilizer application. Integrated nutrient management, involving the combined use of mineral and organic fertilizers will further increase soil organic matter and implicitly improve the effectiveness of mineral fertilizers usage in crop production.

In support of these observations, a study on the impact of tillage and soil amendment was carried out on the most predominant soil (benchmark soil) of the area with the view to recommending the most promising interventions for the study area.

5.3 Soil physical and chemical properties

Fertile and productive soils have the ability to supply nutrients and water to enable plants maximize the climatic resources of a given location. Understanding the physical and chemical properties of the soil is essential for developing measures to sustain higher crop yields.

5.3.1 Soil physical properties

Among the many soil physical properties, soil texture, the proportion of sand, silt and clay in the soil, was studied. Soil texture is an intrinsic attribute of the soil and the one most often used to characterize its physical make up (Hillel, 1998). It correlates with most soil physical properties, including, bulk density, porosity, aeration, structure and water retention and flow.

The 52 soil samples collected from the experimental site were analysed for sand, silt and clay using conventional methods and mapped using GIS to show their spatial distribution with implications for conferment of their properties on the soils they belong.

These sand, silt and clay fractions ranged from 46.52 to 85%; 16 to 40.44% and 1.22 to 12% respectively. The fractions were fitted into the soil textural triangle to facilitate the production of a soil texture map.

The latter map showed the 24 soil units at the study site to belong to four soil types based on texture. These were sand, sandy loam, loam, loamy sand occupying 5.42%, 77.94%, 8.84% and 7.8% respectively.

The loamy sand occurred as two patches at the south-eastern border of the study site and adjoining the southern part of the eastern plateau, while the loam borders the eastern part of the north-western plateau. The sand occupied the northern edge of the south-eastern plateau. The rest of the area, apart from the plateaux, consisted of sandy loam. The latter soil, which occupied the largest area, is therefore the major soil type in the area and may be termed and used as a "benchmark soil" for field experimentation on integrated soil fertility management to address the low soil fertility problem of the study site.

The different soil types present important implications for their management for soil water and nutrient conservation as well as fertility.

As sandy soils, they generally have high bulk density, infiltrability and hydraulic conductivity and low water holding capacity. Values for these parameters, however, differ with the texture. Typical values (Landon, 1994) for bulk density are 1.2 to 1.8 Mg m^{-3} for sands and sandy loam. Infiltration rates (cm h^{-1}) range from 0.1 to 2.0, 1.0 to 8.0 and 2.0 to 25 for loam, sandy loam and sand respectively. The ranges of values for hydraulic conductivity (cm h-1) are 6-12, 12-25 and 25-50 for sandy loam, loamy sand and sand respectively. Available water capacity (mm m^{-1}), on the other hand, vary from 80 for sand, through 120 and 150 for loamy sand and sandy loam, to 170 for loam.

The management of these soils should be directed at practices that will optimize soil infiltrability and hydraulic conductivity, reduce erosion, enhance soil moisture storage and reduce non-productive evaporation losses. Such sustainable land management practices include reduced tillage, plough-plant, ridge and furrow system, tied ridging, zai, circular bunds, mulching and appropriate residue management to add organic matter to the soil.

5.3.2 Soil chemical properties

5.3.2.1 Variability and spatial dependency of soil chemical properties

Alongside the soil physical properties, the samples were analysed for selected chemical properties. These were pH, organic carbon N, P and K. The values were used in a GIS domain to produce maps to show their individual spatial distribution and an overlay to produce the soil fertility map of the study area. The database and the maps may be used to dynamically monitor changes in soil properties as they undergo different management practices. This will inform what changes are required in soil and nutrient management strategies to meet the unavoidable changing trends with time.

To get a general idea about the variation in the different parameters measured, their values were analysed statistically for measures of variability/dispersion about their means. These included standard deviation, coefficient of variability, skewness and kurtosis. These measures presuppose all variation to be spatially independent which do not accord with reality.

In order to quantify the spatial distribution and dependency of the measured variables, kriging was used. It calculates local values from sample data of properties that vary in space and facilities the quantification of spatial dependency among sampling points for a given variable and to obtain unbiased estimates of interpolated values. It also estimates the values at unsampled places of the parameters measured as indicated by the predictive equations in section 4.3.2.2 Semi-variograms were used to describe the way the variance of the parameters changes as the distance separating any two points vary. The results of the analysis are discussed below.

According to Warrick's (1998) guidelines for variability classes of soil properties, pH had a low variation (CV < 15%), P an N medium variation (15% < CV< 50%), and SOC and K, high variation (CV > 50%).

The skewness values (< 0) indicated that most of the pH values tended to be greater than the mean (5.47) with few extreme values of strongly acid conditions. The N, P, K and C (skewness values > 0) had most values less than the mean with a few relatively higher values.

The kurtosis values (< 0) indicated highly dispersed values with greater variability as recorded for C, K and N. The kurtosis values (> 0) indicated less dispersed values, most of which were concentrated around the mean with less variability. The pH and P were in this category.

The spatial variation in the measured parameters and their magnitudes provide the basis for varying management practices, such as fertilizer application rates at the different sites. The magnitude of variation as quantified by the CV and kurtosis helps to explain observed spatial differences in crop growth and yield. The skewness, on the other hand, indicates the magnitude of the parameter values relative to the mean and guides the focus of soil fertility management strategies. In the case of pH, where most values were greater than the mean, lime requirement to raise the pH to, for example 5.5, would be greater for the area with extreme acidic conditions (<5.0) than those with moderate acidity (>5.0).

For N, P, K and C, although the values were generally low most of them, covering a greater part of the area, were still lower and would require relatively more intensive replenishment measures than the area with few extreme and relatively high values.

The data was further examined for normal distribution using the Anderson Darling Test to meet the requirement for kriging. The best fitted models were Gaussian and exponential. The results provided information on the degree of dependency of the measured parameters, N, P, K, pH and SOC.

The interpretation of variogram is very important in kriging. In all cases the variance increased with increasing lag distance, corresponding with more or less strong correlation or spatial dependence at the shortest distances. The variograms increased till it reached the sill variance, i.e. where the variance is constant. The sill variance ranged from 0.0005 to 1.061 for K and P respectively. It represents the degree of the overall spatial variability including random and structural variabilities.

The range, i.e. the distance at which the sill is reached, varied from 1185.47 to 2090 m for pH and K respectively. It marks the limit of spatial dependence.

The nugget on other hand is the distance from the x-axis to the point where the variogram has a positive intercept on the y-axis and reflects the degree of random variability. It also indicates the variation within shorter distances than the sampling interval. The nugget was in a decreasing order of P > N > pH > K with a range of 0.0002 to 0.310

The ratio of the nugget to sill (Co/C+Co), is indicative of the ratio of random variability to overall spatial variability.

A ratio < 25% indicates a strong spatial autocorrelation and dependence as exemplified by C. When the ratio is 25% < (Co/C + Co) < 75%, it is medium autocorrelated and dependence as exhibited by pH, P and K. A ratio >75% depicts weak autocorrelation and dependence, as recorded by N.

The magnitude of dependency facilitates aggregating areas with similar characteristics and which would therefore require the same treatment (eg. Nutrient level, organic amendment, liming) in contrast to areas which are spatially independent due to separating distance.

5.3.2.2 Spatial distribution and mapping of soil nutrients

The pH of the soils ranged between 4.7 and 6.1. Following the classification in Landon (1991), the values were grouped into three classes for mapping purposes. These were very strongly acidic (4.5-5.0), strongly acidic (5-5.5) and moderately acidic (5.5-6.0) with their respective areal coverage of 114 ha. 702.19 ha and 345.04 ha.

The low pH may be due to the losses of basic cation and other nutrients through erosion, leaching and crop uptake and harvest without replenishment and poor crop residue management which leads to low levels of SOM.

The very strongly to strongly acidic conditions have implications for nutrient availability and management. The low pH is favourable for aluminium and manganese toxity for plant growth and deficiency and/or unavailability of plant nutrients such as P, Ca, K, Mg and Mo as observed by Tisdale et al. (1985) and Wang et al. (2006). Under such conditions, bacterial activity is reduced and nitrification of organic matter is significantly retarded (Landon, 1991). Sivarugu and Horst (1998) also reported that in acid soils, excess aluminium primarily injures the root apex and inhibits root elongation. The poor root growth leads to reduced water and nutrient uptake with a consequent reduction in plant growth and yield. The acidic conditions of the soils in the study area therefore present a major constraint to the production of crops by the smallholder farmers who depend mainly on rainfall and the nutrient stocks of their soils for production. Nutrient management of the soil for sustained crop growth and yield should therefore be directed at strategies to address the acidity problem through liming and organic matter management, taking into consideration the spatial magnitude of pH at the study site.

Soil organic carbon (SOC) is an indicator of soil organic matter (SOM) which has important beneficial effects on the physical, chemical and biological properties of the soil. Thus, Maurice *et al*. (1998) used SOM as an indicator of soil fertility, aggregate stability and erosion. As SOM increases, available N, P, K as well as some micronutrients also increase (Oates, 1998). Acquaye (1990) reported that organic matter is the main source of N, P and S for plant growth in no-fertilizer smallholder agriculture. In addition, SOM contributes to enhanced soil infiltrability and water storage and maintenance of stable pH.

These beneficial effects of SOM have eluded the many smallholder farmers at the study area because the soils are very low in organic carbon with values ranging from 0.12 to 0.4%. These values compare with the critical level of 0.6% in Mali (soil water and plant laboratory, Mali) and 2% for tropical soils (Barrows, 1991). According to the latter author, such low levels of SOM are indicative of soil degradation and high risk of soil erosion. The competing uses of crop residues as animal feed which constrain their return to the soil and the general sparse vegetation and intensive cropping may account for the low SOC content of the soils. Farmers should, therefore be encouraged to return as much crop residue as possible to the soil in addition to application of manure and compost. There is the need to search for local leguminous plants which produce large quantities of biomass but not eaten by livestock for possible inclusion in smallholder farming systems.

Soil nitrogen was found to be one of the major limiting nutrients constraining crop growth and yield at the study site. The very low levels (0.01-0.03%) of N are not surprising considering its close association with SOM, which was also very low. The general high hydraulic conductivity of sandy soils could cause leaching of the nitrate and ammonium N to reduce the N level in the soil. The situation is exacerbated by the intensive cropping of the area to continuous cereals (sorghum and millet) without replenishing the depleted nutrients.

Available phosphorus was similarly very low with values ranging from 2.2 to 5.5 mg kg^{-1}compared to the eritical level of ≤ 7 mg kg^{-1}(LSEPi, 2008). The low level of organic matter, the very strongly to strongly acidic conditions and uptake without replenishment may account for the low level of P in the soils of the study site.

For the same underlying reasons of very low organic matter, the sandy soils, with low clay content, high hydraulic conductivity and nutrient losses through leaching and erosion without replenishment, the K levels of the soil were also low.

The overlay of N, P, K and C maps produced a generalized soil fertility map with low level of fertility. The fertility status of greater part of the area was very low. This is indicative of the very low levels of nutrients recorded in the soils of the area. Sustainable crop production in the Siguidolo area can be achieved only through the development and implementation of integrated soil fertility management strategies. Of prime importance is the soil acidity problem, which is a major constraint to nutrient availability and uptake with resultant decreases in crop yields.

In this regard, integrated nutrient management involving the combined use of mineral fertilizers and organic amendments offer better soil fertility replenishment opportunities (Swift, 1997; Traore, 2003)

Sound soil fertility management, as recommended by Quansah (2000), should therefore use available livestock and poultry manure and crop residues wherever practical, taking appropriate nutrient credit for these materials and using mineral fertilizers to balance the crops nutritional requirements for realistic yield goals.

This will require a set of accompanying soil conservation and water utilization technologies. These include ridge furrow system, tie-ridging, circular contour bunds, zai, cereal legume rotations and residue management. The current practice of ridging for water harvesting, use of household waste and mineral fertilizers, though lower than recommended rates, and the emerging millet/sorghum-groundnut/cowpea rotation intercrop in the study area should be fine-tuned into implementable and affordable package for the smallholder farmers. In contributing to this effort, the dynamics of the cropping systems in the study area was studied to show trends as a basis for recommending sustainable cropping systems within the biophysical and socio-economic circumstances of the farmers.

5.4. Impact of tillage and soil amendments on the selected soil chemical properties.

5.4.1 Effect of tillage and soil amendment on pH and soil organic carbon

The strongly acid conditions of the major soil of the study site, on which the experiments were carried out presents adverse conditions for the availability of most of the nutrients needed for plant growth and yield. Under such conditions phosphate ions combine with iron and aluminium to form compounds which are not readily available to plants. Any intervention that will enhance pH to about 5.5 and above has the potential to improve nutrient availability with a resultant increase in crop growth and yield.

In 2013, tillage tended to slightly increase pH but more so by ridge tillage under sorghum. In 2014, the initial pH of 4.78 of the soil increased by 10-12% and 7.2-8.8% under the ridge and hoe tillage respectively. However, the impact of the two tillage practices did not differ significantly ($P<0.05$). Soil amendments also generally enhanced soil pH but more significantly in 2014 with P_4 ranking highest at 5.56, and 5.58 under millet and sorghum. These correspond to a percentage increase in the initial soil pH of 13.3 and 14.3%. These values compare with 10% and 8% under sole Profeba. The increase in pH under TPR than lime could be explained by the time of lime application before planting. Lime should be apply 6 months before planting however in the case of this study it has been apply just before planting. The best tillage x soil amendment interaction (P_3R_1 and P_2R_2) under millet in 2013 increased soil pH by 9% and 5% under ridge and hoe tillage respectively than the initial level (4.78).

The low soil organic carbon content of the major soil of the study site, on which the experiments were carried out, is indicative of poor soil conditions for plant growth and yield, According to LSEP (2008), any intervention that will enhance soil carbon to about 2.3 % has the potential to increase crop growth and yield.

In 2013, tillage decreased soil organic carbon under both ridge and hoe tillage. In 2014, the initial carbon of 0.4 of the soil increased by 18 - 23% and 1-11% under ridge tillage for sorghum and millet respectively. The corresponding values under hoe tillage were 11.1% and 21.6%. However, the impact of the two tillage practices did not differ significantly ($P>0.05$). Soil amendments generally enhanced soil carbon significantly in 2014 with P_4 and P_3 under millet and P_3 under sorghum ranking highest at 0.54 and 0.53 respectively under millet and sorghum. These correspond to a percentage increase in the initial soil carbon of 16.6% and 15%. These values compare with 10% and 8% under P_1. These results accord with those of Doumbia *et al.* (2009) who observed an average increase of 12% per year in soil organic carbon under ridge tillage. Lashermes *et al*. (2009) also stated the addition of exogenous organic matter like compost results in an enhancement of soil organic carbon storage.

5.4.2 Effect of tillage and soil amendment on soil Total Nitrogen, Available Phosphorus and Exchangeable Potassium

The Nitrogen content was low on the major soil of the study site, on which the experiments were carried out. Nitrogen usually has a greater effect on crop growth, yield and crop quality. The low nitrogen content would therefore affect plant growth and yield. Any intervention that will enhance soil nitrogen to the adequate level of 0.13 to 0.23% (Soil Testing Guide, 2013) has the potential to increase crop growth and yield.

The impact of tillage and soil amendments on N content was not consistent. There did not appear to be any significant change in the initial very low N content under both tillage and soil amendments. Apparently, the supply of N from the latter was not even adequate for the growth and yield of the crops to the extent that in some cases the N content of the soil declined. This is indicative of soil nutrient mining when amounts supplied are not sufficient to meet crop demand, thus requiring dependence on the native sources of nutrients for growth. This was exemplified by the 50% decline in the initial total N content (0.02%) of the experimental soil on the control plot (P_0=0.01%); and the Profeba plot (P_1= 0.01%) under millet. Leaching losses of nitrate and ammonium N on the sandy soils may also be implicated in this observation as similarly reported by Vistosh (1995).

On the other hand, Profeba + urea (P_2) and Profeba + urea + lime (P_4) enhanced the initial total N of the experimental plot in 2014 under sorghum. This presumably, may be due to the high N content of the urea complemented by the profeba compost.

The low available phosphorus of the sandy loam on which the experiments were carried out presents adverse conditions for plant growth and yield. Phosphorus is very important for plant respiration, photosynthesis in green leaves, microbial turnover and decomposing litter. Adequate supplies of P are essential for crop quality and strength of straw in cereal. Any amendment that will enhance soil available phosphorus to about 20 mg kg^{-1} (Soil Testing Guide, 2013) and above has the potential to improve crop growth and yield.

In 2013, tillage decreased available phosphorus under both ridge and hoe tillage. The P was however higher under ridge tillage than the hoe tillage under both sorghum and millet.

In 2014, the initial available phosphorus of 2.04 mg kg^{-1} of the soil increased by 1.0% and 37% under the ridge tilled millet and sorghum respectively. The increases under Hoe tillage was 24% under sorghum. However, the impact of the two tillage practices did not differ significantly ($P>0.05$). Soil amendments generally increased soil phosphorus in 2014. The highest phosphorus obtained was under Profeba + TPR + Urea (P_3) ranking highest at 2.47 mg kg^{-1} and 4.01 mg kg^{-1} under millet and sorghum respectively. These correspond to a percentage increase in the initial soil phosphorus of 17% and 49%. These values compared with 1.9% and 17% under sole profeba. The tillage x soil amendment interaction under sorghum in 2014 increased the initial level (2.04 mg kg^{-1}) by 40% and 55% under hoe and ridge tillage respectively. The best tillage x amendment interaction (P_3R_1 and P_3R_2) under sorghum in 2014 increased soil available phosphorus by 40% and 55% than the initial level (2.04mg kg^{-1})

The general improvement of soil available phosphorus could be attributed to the impact of Profeba compost on soil pH. The application of the compost alone increased soil pH by 10 and 8% under millet and sorghum in 2014 and complemented by TPR and Urea to 13 and 14% respectively. The results accord with those of Kalebonye (2011) who found an increase in soil pH and phosphorus availability as a result of kraal manure and liming.

Exchangeable potassium content was low on the major soil of the study site, on which the experiments were carried out. Crops need greater amounts of potassium to achieve their maximum potential yield. Any intervention that will enhance soil potassium content to about 0.20 $cmol_c$ kg^{-1} (LSEP, 2008) and 0.45 $cmol_c$ kg^{-1} to 0.7 $cmol_c$ kg^{-1} (Soil Testing Guide, 2013) and above has the potential to maintain crop health with a resultant increase in crop growth and yield.

The impact of tillage and soil amendments on exchangeable potassium content was not consistent. There did not appear to be any significant increase in the initial potassium content under both tillage practices and soil amendments. Apparently, the supply of potassium from the Profeba was not even adequate for the growth and yield of the crops to the extent that soil potassium declined due to soil nutrient mining.

The decrease in K could be also explained by leaching and K uptake by plants. Haque, (2007) reported that, because potassium ions (K^+) are highly soluble, it easily leaches from soils without colloids. Wang and al., (2013) also explained that in order to achieve its potential maximum yield, plants absorb potassium in greater amounts than any other essential nutrient except nitrogen. The decrease in potassium over the years could be attributed to the higher rainfall recorded in 2014 (932 mm) than 2013 (720 mm). This observation is in accords with that of Lamb (2014) who indicated that high rainfall amounts contribute greatly to potassium leaching in sandy soils.

5.5 Effect of tillage and soil amendment on grain and biomass yields

The low nutrient condition of the major soil of the study site, on which the experiments were carried out, presents adverse conditions for the availability of most of the nutrients needed for plant growth and yield. Under such conditions any intervention that will enhance the overall soil nutrient status and allow crop to achieve its potential yield is recommended. The application of sole Profeba and its combination with Urea, TPR and Lime under ridge tillage and hoe tillage showed general improvement in both biomass and grain yield for both millet and sorghum.

Generally, grain yield in millet and sorghum was greater in 2014 than 2013 due mainly to higher rainfall. This accords with several studies which showed a strong correlation between rainfall and the grain yield of millet and sorghum (Larsson, 1996, Krishna, 2004 and Mijinyaw, 2015).

All the soil amendments also enhanced the grain yield of millet and sorghum in the two seasons. In 2013, the percentage increase in grain yield over the control ranged from 52.9 to 76.5 in the order $P_4 > P_2 > P_3 > P_1$. The corresponding values and trend in 2014 were 62.1 to 69.3 and $P_3 > P_2 > P_4 > P_1$. The percentage increase in the grain yield of sorghum over the control ranged between 72.4 and 85.3 in a decreasing order of $P_2 = P_1 > P_4 > P_3$. The values in 2014 were 90.3 to 92.3 and $P_4 > P_2 > P_3 > P_1$. The impact of soil amendments was therefore greater on sorghum than millet, and even more so under better rainfall. The implication is that sorghum was more responsive to the soil amendments application than millet. The greater yield under the soil amendments over the control could obviously be due to the supply of nutrients which presumably was enhanced under the relatively better rainfall in 2014.

The complementary role of mineral fertilizers and lime in improving the performance of Profeba in increasing grain yield was amply shown by the results. The higher grain yield recorded under the Profeba compost + mineral fertilizer treatments could be attributed to the nutrients being readily available from the fertilizers and the improvement of mineralization of compost with the application of the mineral fertilizers as similarly reported by Zougmore et al. (2003).

The improvement in the pH of the very strongly acidic sandy loam by the Profeba and the lime treatments also presumably contributed to better soil conditions for crop growth and yield as evidenced in the high biomass and grain yield of millet and sorghum.

The significant increases in biomass and grain yield under the ridge tillage may be due to better soil moisture storage and availability as similarly highlighted by Doumbia et al. (2008)

5.6 Effect of tillage practice and soil amendments on sorghum value cost ratio

The value Cost Ratio (VCR) was used to assess the benefit in term of cost of the combined application of profeba with urea, TPR or lime in managing soil nutrients in small holders' farms in Mali. The highest VCR was 1.21 under Ridge tillage, sorghum and Profeba + Urea. Despite its contribution to increased crop yield, the best VCR was less than 2 which is the lower threshold of a profitable enterprise (Heerink, 2005).

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMANDATIONS

6.1 Conclusions

The main purpose of this study was to use remote sensing and GIS as decision support tool for appropriate soil fertility management practices, a key factor for improving soil fertility and increase sorghum and millet yields on smallholder farms in Mali.

The integration of remote sensing, GIS and conventional georeferenced field sampling facilitated the assessment of spatial distribution for mapping of the baseline and dynamic changes in vegetation, soils and their physical and chemical properties, cropping systems and land use. These maps can be used to guide the development and implementation of integrated soil fertility management strategies for sustainable crop production in the Siguidolo area.

The soils are generally sandy with sandy loam covering over 70% of the area. This is considered the 'benchmark' soil of the study site. They are acidic, ranging from moderately to very strongly acidic. The inherent nutrient content and organic matter are generally very low. The soil fertility map pin-points very low fertility hotspots and facilitates the targeting of nutrient replenishment strategies.

The vegetation is characteristically sparse comprising bare, grassland with scattered trees and woodland with grass cover. The former two vegetation types cover about 83% of the area and render the site highly susceptible to erosion by water and wind. The dense woodland tends to be located along the stream courses.

The major cropping system is cereal-based with millet, sorghum and maize as the cereals and cowpea and groundnut as the legumes. The crops are cultivated as sole, intercrops or in rotation. The temporal mapping of the cropping systems facilitated the analysis of cropping systems dynamics over the 2011 to 2013 period.

The fertilizer use in the area is mainly for cotton and maize with the other crops in rotation benefiting from the residual fertility. However, grain yield of millet and sorghum low.

Profeba compost has a potential liming effect, increasing pH from 4.78 to 5.33. When applied sole, Profeba increases grain yield, but its performance is enhanced when combined with mineral fertilizer and lime

All the soil amendments enhanced millet and sorghum yield, but more so under better rainfall conditions. The best grain yield was obtained under P_2 and P_3. Higher millet and sorghum grain yield can be obtained under ridge tillage than hoe tillage in the Siguidolo area. The highest VCR, although less than 2, was obtained under P_2 for millet and sorghum.

6.2 Recommendations

More studies involving the impact of tillage and soil amendments in the experimental site would improve the applicability of the results over the entire area.

Additional studies could be projected to optimize the amount of fertilizers in order to meet the economic aptitude of poor household farmers.

The remote sensing-GIS nexus can be further used to study and map the status of land degradation particularly when linked to erosion models, such as the Universal soil less Equation (USLE).

Practices that enhance in-situ moisture storage, such Zai and bunds need detailed studies to enhance crop productivity under rainfed farming

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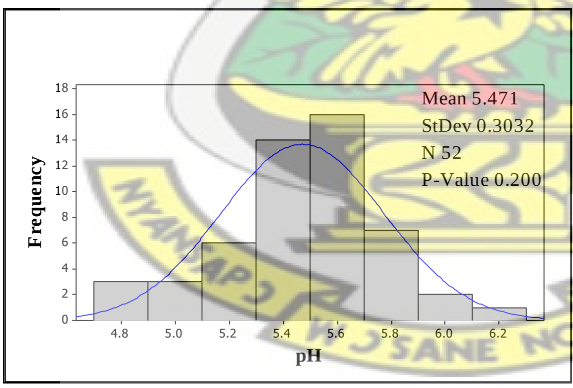
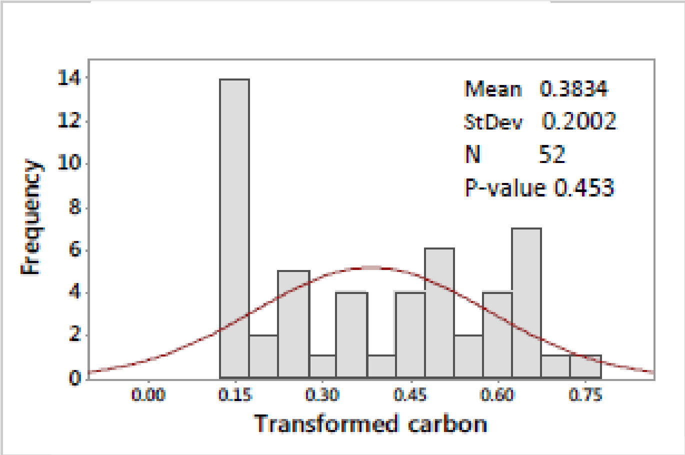
APPENDICES

Appendix 1: Descriptive statistics for the selected soil parameters transformed

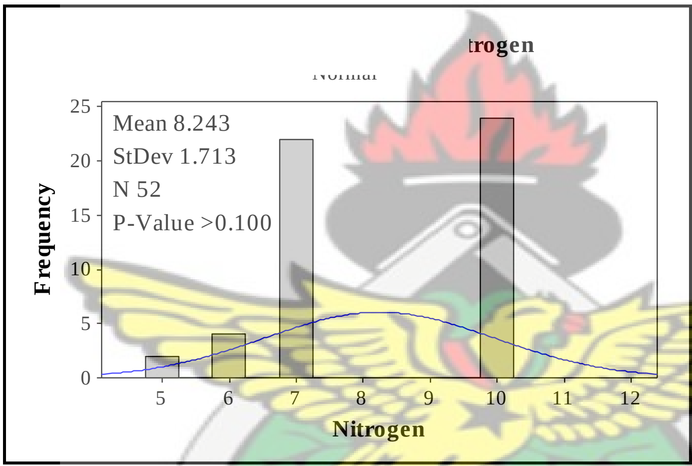
Soil nutrient	**C** **%**	**TN** **%**	**K** **($cmol_c$ kg^{-1})**
Mean	0.38	8.24	7.03
Median	0.37	7.07	7.03
Minimum	0.13	5.00	3.16
Maximum	0.74	10.00	10.00
Coefficient of variation (CV)	52.21	20.78	31.61
Standard deviation	0.20	1.71	2.22
Skewness	0.05	-0.13	0.09
Kurtosis	-1.48	-1.51	-1.22



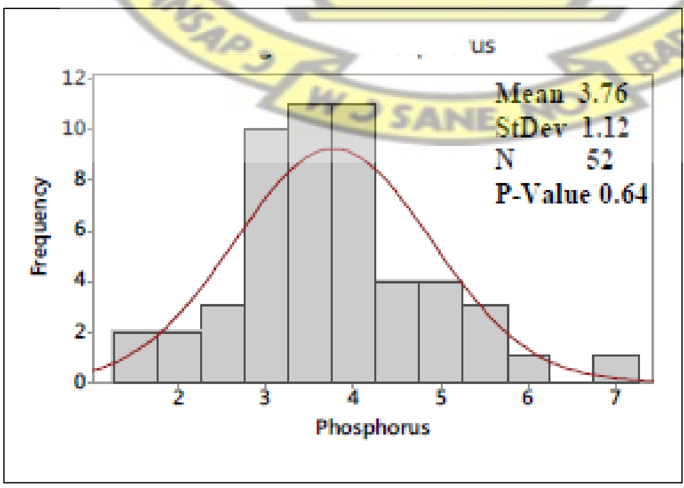
Appendix 2: Histogram of Anderson Darling normality test for pH



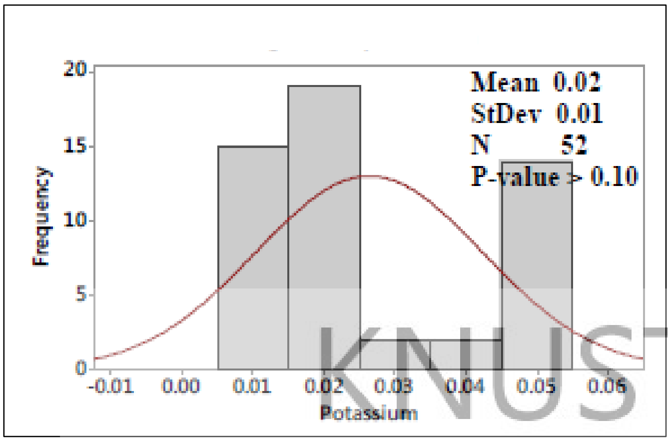
Appendix 3: Histogram of Anderson Darling normality test for Carbon



Appendix 4: Histogram of Anderson Darling normality test for Nitrogen



Appendix 5: Histogram of Anderson Darling normality test for phosphorus



Appendix 6: Histogram of Anderson Darling normality test for potassium

Appendix 7: physical and chemical characteristics of soil units

Soil Unit	Sandy (%)	Silt (%)	Clay (%)	pH (1:1H_2O)	Carbon (%)	Nitrogen (%)	Phophorus (ppm)	Potassium (meq)	Soil Texture
U1	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Plateau
U2	72.63	22.37	5.00	5.60	0.24	0.01	2.60	0.05	
U3	63.34	29.33	7.33	5.27	…	0.01	2.19	0.03	
U4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Plateau
U5	47.34	41.33	11.33	5.55	0.31	0.02	2.92	0.05	
U6	67.00	28.00	5.00	5.62	...	…	2.55	0.05	
U7	58.50	37.50	4.00	5.88	0.26	0.02	3.00	0.13	
U8	62.67	32.00	5.33	5.81	0.17	0.01	3.89	0.06	
U9	60.00	37.00	3.00	5.26	0.10	0.03	3.29	0.07	
U10	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Village
U11	63.00	35.00	2.00	5.39	0.22	0.02	3.65	0.07	
U12	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Plateau
U13	79.68	12.66	7.66	5.24	0.02	0.02	3.89	0.03	
U14	74.60	19.40	6.00	5.52	0.01	0.01	2.00	0.05	
U15	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Plateau
U16	58.00	36.00	6.00	4.89	0.26	0.03	7.31	0.05	
U17	69.00	22.00	8.00	4.90	0.40	0.02	2.92	0.05	
U18	79.50	18.50	2.00	5.29	0.05	0.02	3.65	0.02	
U19	75.00	20.00	6.00	5.22	0.06	0.03	1.46	0.05	
U20	84.67	13.33	2.00	5.55	0.16	0.02	2.40	0.06	
U21	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Plateau
U22	61.50	33.50	5.00	5.68	0.17	0.02	1.00	0.05	
U23	65.00	32.00	3.00	5.66	0.24	0.02	3.65	0.05	
U24	63.00	33.00	4.00	5.65	0.24	0.02	6.00	0.46	
U25	57.50	39.50	3.00	4.85	0.40	0.01	4.38	0.05	
U26	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Plateau
U26	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Hamlet
U27	xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Hamlet
U28	Xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Hamlet
U29	Xxx	xxx	xxx	Xxx	xxx	xxx	xxx	xxx	Hamlet

Appendix 8: Survey form used for onsite measurement and soil sampling

ID	Lat	Long	Position on Topography	Erosion marks	Vegetation	Soil	Humus	Land use
1	-6.785759	12.903181						
2	-6.785734	12906025						
3	-6.784447	12.912178						
4	-6.780503	12.912932						
5	-6.782104	12.914066						
6	-6.783456	12.916329						
7	-6.781895	12.920424						
8	-6.784887	12.922881						
9	-6.786287	12.919713						
10	-6.790212	12.920225						
11	-6.789824	12.916863						
12	-6.792270	12.914029						
13	-6.796103	12.917167						
14	-6.800097	12.918834						
15	-6.799119	12.921507						
16	-6.791992	12.925973						
17	-6.798179	12.926366						
18	-6.796528	12.929871						
19	-6.790306	12.932548						
20	-6.787240	12.933349						
21	-6.789009	12.935480						
22	-6791490	12.936379						
23	-6.794351	12.934108						
24	-6.795493	12.937150						
25	-6.791618	12.939542						
26	-6.788798	12.940447						

27	-6.795493	12.937150
28	-6.799816	12.939563
29	-6802362	12.943748
30	-6.805024	12.945957
31	-6.803508	12.940715
32	-6.798933	12.934691
33	-6.802759	12.933326
34	-6.801103	12.930768
35	-6.807018	12.932822
36	-6.806337	12.929457
37	-6.805010	12.928381
38	-6.802278	12.927422
39	-6.805016	12.925478
40	-6.802130	12.923788
41	-6.807503	12.927580
42	-6.809141	12.924113
43	-6.807789	12.922120
44	-6.810585	12.920348
45	-6.804548	12.920563
46	-6.807553	12.918128
47	-6.812642	12.915427
48	-6.810695	12.915427
49	-6.806316	12.912741
50	-6.809380	12.910761
51	-6.806077	12.909250
52	-6.803136	12.911506
53	-6.802355	12.915490
54	-6.796926	12.910947
55	-6.795698	12.913880

56	-6.790222	12.909655
57	-6.789200	12.911859

Appendix 9: Survey form for mineral fertilizer application in 2014

Nº ID	Household	Mineral Fertilizer (bag)				
	Name	Urea	DAP	Complex cereal	NPK	Other
1	Dougoukolo Diarra	3	0	1	0	0
2	Konzon Diarra	0	0	0	0	0
3	Nientigui Diarra	0	0	4	0	0
4	Niazon Diarra	0	0	4	0	0
5	Bourama Djire	1.5	0	2	0	0
6	Tieblen Diarra	2	0	1	0	0
7	Minkoro Diarra	0	0	0	0	0
8	Baba Diarra	1	0	5	0	0
9	Tete Diarra	0	0	0	0	0
10	Sory Diarra	0	0	3	0	0
11	Zoumana Diarra	0	0	0	0	0
12	Bakary Diarra	1.5	1	1	0	0
13	Morifin Diarra	0	0	0	0	0
14	Bable Diarra	2	1	3	0	0
15	Monzon Diarra	1	0	3	0	0
16	Missema Diarra	2	0	10	0	0
17	Kassim Diarra	1	0	2	0	0
18	Zan Diarra	2	0	3	0	0
19	Mory Traore	0	0	2.5	0	0
20	Cheick Diarra	1	0	3	0	0
21	Massa Diarra	1	0	1	0	0
22	Dougoutiki Diarra	0	0	3	0	0
23	Koke Diarra	0	0	0	0	0
24	Makono Fomba	0	0	1	0	0

25	Bakoniba Keita	0	0	10	0	0
26	Siratigui Diarra	0	0	1	0	0
27	Bafalen Diarra	0	0	2	0	0
28	Ba N'Pe	0	0	1	0	0
29	Bandiougou Diarra	1	0	1	0	0
30	Nama Diarra	3	1	2	0	0
31	Djiriba Diarra	0	0	0	0	0
32	Yacouba Diarra	1.5	0	0	0	0
33	Sounkolo Diarra	1	0	0	0	0
34	Bougouba Togola	0	0	0	0	0
35	Ba N'Golo Togola	2	0	1	0	0

N.B. 1 bag of mineral fertilizer = 50kg

Appendix 10: Survey form for organic fertilizer used in 2014

Nº ID	**Household**	**Organic fertilizers**			
		Compost	**Household waste**	**Crop residue**	**Other**
1	Dougoukolo Diarra	x	x	x	0
2	Konzon Diarra	x	x	x	0
3	Nientigui Diarra	0	x	x	0
4	Niazon Diarra	0	x	x	0
5	Bourama Djire	x	x	x	0
6	Tieblen Diarra	0	x	x	0
7	Minkoro Diarra	0	x	x	0
8	Baba Diarra	0	x	x	0
9	Tete Diarra	0	x	x	0
10	Sory Diarra	0	x	x	0
11	Zoumana Diarra	0	x	x	0
12	Bakary Diarra	0	x	x	0
13	Morifin Diarra	0	x	x	0
14	Bable Diarra	0	x	x	0
15	Monzon Diarra	0	x	x	0
16	Missema Diarra	0	x	x	0
17	Kassim Diarra	x	x	x	0
18	Zan Diarra	0	x	x	0
19	Mory Traore	0	x	x	0
20	Cheick Diarra	0	x	x	0
21	Massa Diarra	0	x	x	0
22	Dougoutiki Diarra	0	x	x	0
23	Koke Diarra	0	x	x	0
24	Makono Fomba	0	x	x	0
25	Bakoniba Keita	0	x	x	0

26	Siratigui Diarra	0	x	x	0
27	Bafalen Diarra	0	x	x	0
28	Ba N'Pe	0	x	x	0
29	Bandiougou Diarra	0	x	x	0
30	Nama Diarra	0	x	x	0
31	Djiriba Diarra	0	x	x	0
32	Yacouba Diarra	0	x	x	0
33	Sounkolo Diarra	x	x	x	0
34	Bougouba Togola	0	x	x	0
35	Ba N'Golo Togola	x	x	x	0

Appendix 11: Survey form for yield in 2014

Nº ID	Household	Yield bag ha^{-1}		Yield with mineral fertilizers	
		Millet	Sorghum	Millet	Sorghum
1	Dougoukolo Diarra	10	0	13	0
2	Konzon Diarra	0	3	0	0
3	Nientigui Diarra	0			
4	Niazon Diarra	5	4	7	5
5	Bourama Djire				
6	Tieble Diarra	3	1.5	3	1.5
7	Minkoro Diarra	3	1	0	0
8	Baba Diarra	8	5	10	7
9	Tete Diarra	0	2	0	0
10	Sory Diarra	7	0	8	0
11	Zoumana Diarra	0	4	0	0
12	Bakary Diarra	0	7	0	8
13	Morifin Diarra	3	0	4	0
14	Bable Diarra	4	2	6	2
15	Monzon Diarra	10	8	12	8
16	Missema Diarra	7	8	8	10
17	Kassim Diarra	10	4	12	5
18	Zan Diarra	7	0	10	0
19	Mory Traore	5	3	7	0
20	Cheick Diarra	0	2	0	2
21	Massa Diarra	4	3	5	4
22	Dougoutiki Diarra	6	2	8	2
23	Koke Diarra				
24	Makono Fomba	0	6	0	0
25	Bakoniba Keita	7	8	13	10
26	Siratiki Diarra	3	0	4	0

27	Bafalen Diarra	0	2	0	3
28	Ba N'Pe	3	4	0	0
29	Bandiougou Diarra	0	10	0	0
30	Nama Diarra	4	5	5	6.5
31	Djiriba Diarra	6	7	0	0
32	Yacouba Diarra	0	5	0	6
33	Sounkalo Diarra	6	5	6	6
34	Bougouba Togola	7	3	0	0
35	Ba N'Golo Togola	7	0	8	0

Appendix 12: Landsat image of the study area

Ground overview of soil units with sparse vegetation

Appendix 13: Pictures of the study area