

**ASSESSMENT OF THE SUITABILITY OF SOME SOILS OF THE FOREST-
SAVANNA TRANSITION AND THE INTERIOR SAVANNA ZONES FOR MAIZE
PRODUCTION USING SOIL QUALITY RATING, CROP MODELLING AND
MULTI-CRITERIA APPROACHES.**

BY

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PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF
M.PHIL SOIL SCIENCE DEGREE**

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DECLARATION

I do hereby declare that this thesis has been written by me and that it is the record of my own research work. It has not been presented for another degree elsewhere. Works of other researchers have been duly cited by references to the authors. All assistance received has also been acknowledged.

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DEDICATION

This thesis is affectionately and humbly dedicated to my wife, Jacinta Nketia, my daughter, Nhyira Yaa Pokuaa Abrefa-Nketia, my siblings namely Osei Kwame, Akwasi Agyemang, Osei-Poku Jnr and Ida Osei-Peprah. A special feeling of gratitude to my loving parents, Mr. J. K. Osei and Mrs. Adwoa Pokuaa Nketia, whose words of encouragement and push for tenacity ring in my ears and to all those who took interest and encouraged me in my academic pursuit.



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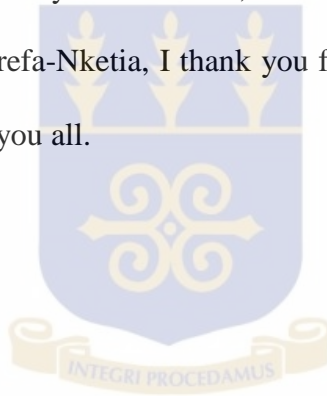
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ABSTRACT

Eight soil series from two agro-ecological zones of Ghana were evaluated for their suitability for maize production intensification using three approaches: the Soil Quality Index (SQI), DSSAT yield simulations and the Multi-criteria Analysis (MCA). Four of the series were from the Forest – Savanna Transition namely Wenchi series (Feric Dystric Leptosol), Ejura series (Haplic Lixisol), Damongo series (Dystric Nitosol) and Lima series (Eutric Gleysol). The four soils from the Guinea Savannah were Mimi series (Haplic Lixisol), Verempere series (Ferric Luvisol), Kpelesawgu series (Eutric Plinthosol) and Kupela series (Eutric Gleysol). The SQI rating considered soil properties such as bulk density, pH, organic carbon, total nitrogen, available phosphorus and water holding capacity. For DSSAT, the impacts of weather variability were considered in addition to soil and management factors. The MCA evaluation expanded the criteria to include economic factors such as price, input and labour costs, soil erosion and conservation factors as well as distance to market. All the approaches led to different ranking of the soil series. The SQI results rated the soil series in the order: Damongo > Kupela > Mimi > Verempere > Lima > Ejura > Wenchi > Kpelesawgu. The ranking by DSSAT was: Lima > Kupela > Mimi > Ejura > Damongo > Kpelesawgu > Verempere > Wenchi. Yield stability was lowest for Lima (7%) and highest for Verempere (131%). Using the MCA, the ranking was: Damongo > Mimi > Lima > Ejura > Verempere > Wenchi > Kpelesawgu > Kupela. In spite of the differences in ranking of the soils by the three systems, Damongo was the “best” in two cases (SQI and MCA). It was however not the best for DSSAT mean yield. It showed a yield variability average of 49%. Based on the results, Damongo, Mimi, Lima and Ejura soil series could be considered suitable for maize intensification, whereas the other soils may be considered as marginal. The study showed

that the soils in the forest - savanna transition zone (Brong Ahafo) is more suitable for maize production than those of the guinea savannah (Northern Region) zone.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Maize (*Zea mays*) is a major staple food crop in Ghana and accounts for 1.8 million metric tons of domestic consumption (Index Mundi, 2015). The food crop has however experienced a decline growth of 5.26% of food consumed (Index Mundi, 2015). Although it is traditionally grown mainly in the southern zones of Ghana, it has spread to many forest-transition and guinea savanna zones, apparently due to crop breeding efforts. The yields of maize are significantly higher than the other cereals (millet, sorghum). The capability of soils to produce food on sustainable basis is fundamental to the survival of mankind (Mueller et al. 2010). However, not all soils have this capability. Therefore, it is necessary to assess both the potential of soils in terms of their properties and also management practices so as to determine the “best” practices that should be extended to farmers. Hitherto, identification of locations to intensify maize production has been based on land or soil suitability classification methods.

Soil management has become paramount due to global environmental changes (Lal, 2008; Mueller et al., 2010). Thus, changes in land use and land cover are also important in the study of global environmental change (Meyer and Turner, 1994). Due to the fact that climate change and climate variability pose a threat to lives and livelihood, their direct effects on soil suitability analysis (SSA) and landuse planning (LP) are critical. Paschal et al. (2013) reported that climate change and climate variability have affected the state of agricultural productivity in Ghana and could result in food insecurity. There is the need to address these global concerns of climate change and climate variability (Stocker, 2000; Parry et al., 2007; Meehl et al., 2007; Paschal et

al., 2013). Unfortunately, although the rural poor-resource farmers are the least contributors to the factors causing rising temperatures and rainfall variability, they suffer the most of the consequences of climate change (Kalogirou, 2002).

Forty percent of the economy, 75% of export earnings and 60% of the labour of Ghana are from the agricultural sector (Quiñones and Diao, 2011). Also, as indicated by Aryeetey and McKay (2004), agriculture has been the backbone of Ghana's economy and the main driver of growth over the last two decades. Ghana's agriculture is predominantly smallholder, traditional and rain-fed with farm sizes ranging from 0.5 to 1.2 hectares and are noted for low use of improved agricultural technology (Yiridoe et al., 2006; Chamberlin, 2008).

Although Ghana's crop yield growth rate is 17%, 5% of every 1.2 million Ghanaians have insufficient and limited access to nutritious food (METASIP, 2010). Paschal et al. (2013) indicated that climate change is affecting mainly the savannah areas in the north and to some extent the forest transitional agro-ecological zone (AEZ) of Ghana. Due to the fact that the effects of climate change on agricultural productivity and poverty are closely related (Eriksen and O'Brein, 2007), there is the need to give serious attention to variability in drought and rainfall patterns so as to mitigate their effects.

In order to adapt to climate change variabilities so as to mitigate their impacts, a detailed understanding of the complex intertwined structures of soil properties need to be studied and matched with landuse management interventions and economic interventions. Many scientists use the Boolean suitability analysis (Burrough et al., 1992; Hall et al., 1992; Ahamed et al., 2000; Collins et al., 2001) to develop land suitability schemes in landuse planning. However, management recommendations required to provide rural-poor resource farmers with requisite

information and management interventions are still inadequate. Farmers therefore have limited capacity in producing to attain food security.

The Ministry of Food and Agriculture (MoFA) of Ghana in collaboration with the German Agency for International Cooperation (GIZ) is implementing a project entitled Adaptation of Agro-ecosystems to Climate Change (AAESCC) (Paschal et al., 2013). This project was started in 2012 with the main objective to reduce climate-related yield losses to farmers and incorporate the results of the measures into agricultural sector policy on adapting land-use systems to climate change. It is envisaged that pilot measures would be developed in the guinea savannah and forest transition ecological zones to help shape agricultural sector policy and national programmes in adapting land-use systems to climate change (Paschal et al., 2013).

1.2 Problem Statement and Justification

Booth and Jackson (1997) and Zeleke and Hurni (2001) indicated that as long as the magnitude of resource degradation of the present landuse systems and cost of various resource management strategies are hardly known, it is difficult for any decision maker to allocate scarce funds and resources efficiently. Although, institutions in Africa have incorporated programmes and institutional linkages to give priorities to agriculture with the aim of improving food security for the most vulnerable (small holder farmers, particularly women), soils in the agricultural ecosystem are continually being subjected to major disturbances (Hobbs and Huenneke, 1992). Women in most African countries are the main farmers who produce food crops, while men produce export and cash crops (Gladwin, 2002). About 70 – 80% of the domestic food supply is mainly produced by women and about 46% farmlands are also cultivated by women

(Gladwin, 2002). Although not the focus of this work, the gender impacts on soil management should not be overlooked.

Low agricultural productivity lies at the heart of continued widespread hunger and poverty in Africa (Haggblade and Tembo, 2003). Among all the developing regions, it is only in Africa that agricultural productivity growth has failed to keep pace with population over the past five decades (Haggblade and Tembo, 2003). It is widely noted that increased agricultural productivity by incorporating good nutrient balance management offers a potential powerful tool for reducing poverty in Africa (Diao et al., 2008; Mitchell, 2008). Furthermore, Ferrari (1989) indicated that drought would not necessarily lead to famine if the region's natural resources are properly managed. It is when ecosystems are stretched to the limit and when over population and poor economic circumstances prevail that the poor and natural resources become most vulnerable (Ferrari, 1989).

In Ghana, the government recognizes the urgent need to boost smallholder productivity in order to minimize poverty and spur economic growth (Langyintuo, 2011). The policies of the government are geared towards reducing problems faced by smallholder farmers in their farming activities. Such problems include access to good seeds, fertilizers and other agricultural inputs and ready markets. In addition to cultural difficulties in attaining high agricultural productivity, site specific soil management problems associated with climate change and climate variability are critical.

The Northern and Brong Ahafo regions of Ghana can be described as primarily sparsely populated and with the majority of the population being rural and mainly agrarian (Paschal et al., 2013). Given that agricultural growth has been attributed to land mass expansion rather than increased yields and improved crop quality (Diao and Sarpong, 2007), the rural poor-resource

farmers require soil quality information and management schemes that would improve livelihood and ensure improved agricultural productivity.

Consumption of cereals, root, tubers and other food crops varies substantially in Ghana (SRID, 2008). SRID (2008), reported that average yields (production) of food crops namely cereals (5.4%), root and tuber crops (49.9%), legumes (2.9%) and others (41.8%) from 2002 – 2008 were generally low. There is therefore the need to provide requisite information to farmers so that they can improve production.

Karlen et al. (2003) indicated that the use of soil information for optimum productivity is key to any agricultural activity. Furthermore, in identifying soil management interventions, it is essential to consider the soil in its present state and improvement that will occur after management interventions. Even if a location has a good soil quality rating and yield stability, the investor community which is often economic oriented require further information such as nearness to market, labour and other input costs, soil conservation practices, among others, in order to assess the economic viability of cropping ventures (Janssen and Herwijnen, 2007). Thus, the overall evaluation and selection of a location for intensive maize production must consider these additional factors, beyond soil and weather factors only. For this reason, appropriate tools are required. The Multi-Criteria Analysis (MCA) provides such a tool for decision making for complex problems (Janssen, 2001; Janssen and Herwijnen, 2007; Mysiak et al., 2005).

It is envisaged that upon completion of this study, a guideline, good decision support information and a planning tool would be developed for physical planners at the districts, and also for commercial farmers (rainfed and irrigation) and forestry organizations. Also, smallholder traditional farmers who are farming in ecologically fragile environments would

adapt to the adverse effects of climate change and climate variability. Also, such information would be an added-on benefit to the 80% small scale farmers (METASIP, 2011), as soil and soil suitability maps represent overviews of soil capability for any agricultural land-use. Thus, decision support information would be important for hunger mitigation, poverty reduction, improving rural livelihood and promotion of agricultural economic growth (Karlen et al., 2003). Furthermore, soil suitability assessment and maps would provide guidelines regarding the quantity of farm inputs (e.g. fertilizer) needed, resource allocation and where appropriate management and conservation interventions should be implemented. Hence, the guidelines would serve as a source of information to aid decision making in farming, establishment of pastures, general investment and also supplement existing information on soil suitability and management.

1.3 Research Objectives

The main objective of this study was to generate information and provide management recommendations to rural poor-resource farmers with the view to helping to maximize soil resource use, improve agricultural productivity and maximize returns on farm inputs.

The specific objectives of the study were to:

- Characterize the dominant soil series in the study areas in the Brong Ahafo and Northern regions,
- Determine the overall suitability of the dominant soils for maize production using SQI, DSSAT and an MCA tool, and

- Produce digitized soil suitability classification maps to indicate appropriate management options.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Importance of Information on Suitability of Soils for Crop Production

Soils are non-renewable resource and they serve unlimited purposes (Blum, 2006). Thus, it is important to investigate their capability to function to inform appropriate use. Furthermore, there is the need to build soil information and make it accessible for decision making. According to Lal (2008) and Hillel (2009), soils are the basis of human survival in terms of food supply and the provision of ecological and social functions. Moreover, as reported by Borlung (2007), to alleviate poverty and improve human health and productivity would require dynamic agricultural development. Although there is the need to improve productivity, the soil's capability to function cannot be stretched beyond its bearing capacity (Cassmann et al., 2003). Mueller et al. (2010) also raised questions on how (1) soil properties affect productivity, (2) soil classification information is vital regarding soil productivity and (3) method of soil assessment is appropriate in productivity investigation. As indicated by Larson and Pierce (1991) and Karlen et al. (2003) no one form of soil information is adequate to address these questions. Moreover, suitability of soil to function is not restricted to landuse and crop productivity only. Thus, there is the need for adequate information on the capability of soil to aid management and productivity (Bockstallar et al., 2009; Hillel, 2009).

In this study, the major focus is to evaluate soils for their suitability for intensive maize production. Maize (*Zea mays*) is a major staple food crop in Ghana and domestic consumption accounts for 1.8 million metric tons (Index Mundi, 2015). Maize also accounts for 50 – 60% of total cereal production (MiDA, 2010). This staple food crop has experienced a decline growth

of 5.26% of food consumed (Index Mundi, 2015). Although maize is traditionally grown mainly in the southern zones of Ghana, it has now spread to many forest-transition and guinea savanna zones of Ghana, apparently due to crop breeding efforts (MiDA, 2010). The yields of maize are significantly higher than those of the other cereals (millet, sorghum) grown in Ghana (SRID, 2008). Yields of maize are below their attainable yield levels (Index Mundi, 2015). Averagely, Ghana obtains 1.5 Mt maize per hectare whereas, yields as high as 5.0 – 5.5 Mt per hectare can be realized when improved seeds, efficient use of fertilizer, irrigation and good soil management are adopted (MiDA, 2010). Generally, Ghana's vast resources of agricultural lands are ideal for commercial maize production. However, 70% of the domestic maize supply and consumption have experienced a continual deficit of about 84,000 to 144,900 Mt since 2005 to 2008 (METASIP, 2011). It has been reported that between 2010 and 2015, maize demand is projected to grow at an annual compound growth of 2.6% (MiDA, 2010). In 2009, it was reported that about 35% of maize produced was lost along the value chain (MOFA, 2009). MiDA (2010), further reported that Ghana is not self-sufficient in either of its two most important staple crops (maize and rice), as the country has experienced average shortfalls of 12% for maize supplies and 69% rice supply in recent years. Maize average yield was 1.9 Mt ha⁻¹ against an estimated achievable yield of around 2.5 to 4 Mt ha⁻¹ (MoFA, 2010). It has been identified that gaps between achievable yields (under best farmer practices) and actual yields is about 37%. These low yields could be partly attributed to problems associated with maize production in the Guinea savanna and Forest transitional agro-ecological. As such, the Government of Ghana has identified interventions to be used to increase the production of maize through intensive methods such as use of certified seeds and Good Agricultural Practices (GAPs) amongst others, to meet the growing demand for maize and improve food security.

2.2 Soil Profile Description

Soil profile is the vertical cross section of the soil that may show horizontal layers called horizons. Each profile has unique horizons in terms of arrangement and characteristics. Description of soil profiles provide information on the nature, physico-chemical properties and possible functions of the soil as part of the landscape (Vanmarcke, 1977). Description of soil profiles provides (1) a format for presenting information gathered during investigation and testing, including site and soil date, (2) the basis for predicting performance and for quantifying the reliability of performance predictions (Vanmarcke, 1977).

2.3 Soil Quality and Information on Soil Suitability Classifications

2.3.1 Soil Quality

Soil quality is the measure of soil's capacity to support a specific kind of requirement within a natural or managed ecosystem boundaries in sustaining human need or purpose and plant productivity (Doran and Parkin, 1994; Bone et al., 2010; Gómez-Sagasti et al., 2012). The importance of soil quality is not limited to only comparing soils to processes, but key to biological, chemical and physical processes of the soil (Larson and Pierce, 1991; Karlen et al., 2003; Roger-Estrade et al., 2009). Rossiter (1996), emphasized that soil is one vital component of land resource and hence, measures should be developed to manage it.

A number of research works in Ghana have employed the SQI to map the productivity of crops. For example Boateng et al. (2000) and Boateng (2005) used GIS databases and SQI as tools for land suitability assessment for rice production in Ghana. Also, Boateng (2005), indicated that mapping procedures that used SQI can be adopted to map the productivity of any other crops in Ghana. Braimoh et al. (2004) also used soil quality indexing for land evaluation for maize

production based on fuzzy set and interpolation. It was suggested however that the fuzzy techniques was helpful for land evaluation when subtle differences in soil quality indexes were of major interest in mapping productivity of crops (Braimoh et al., 2004). Ziblim et al. (2012), used productivity index (PI) to rate 3 soil series in the Tolon/Kumbungu district of the Guinea savanna AEZ. Productivity Index (PI) of the soils were presumed to be an indicator of the productive potential of the soils. Ziblim et al. (2012), also suggested that soil physical and chemical properties based on PI could be used to quantify the productivity of soils. However, they concluded that the inclusion of organic matter, soil pH and CEC into the determination of PI proved to be more efficient (Storie, 1976). They therefore recommended the incorporation of crop residue into soil, in addition to inorganic fertilizer use and crop rotation practices in our farming practices.

2.5 Modelling of Crop Yields Using DSSAT

Crop production is an integration of soil, plant and weather inputs. Thus, the suitability of a given soil for food production cannot be based on soil suitability alone. Crop models, therefore seek to predict growth, development and yield as a function of local weather, soil conditions and crop management (McCown et al., 1996; Jones et al., 2003). The Decision Support System for Agrotechnology Transfer (DSSAT) suite of crop models are among the most widely used in the world for yield prediction. The output of crop models may be used to identify soil-crop suitability maps. Furthermore, results could be compared with actual yield data and their productivity index evaluated (Storie, 1976; Jones et al., 2003).

Bowen et al. (1998) used DSSAT to simulate cropping sequences and found that the model enhanced crop production and improved management interventions at site-specific levels. Also,

DSSAT was used to predict changes and detect trends in crop yield, nutrient levels and uptake as a way of identifying management practices that are potentially sustainable or unsustainable (Bowen et al., 1998). Hoogenboom et al. (2004) reported that the DSSAT modelling tool integrates the effects of soil, crop, weather and management options into an appropriate management recommendation.

A number of researchers have employed the crop modeling approach to evaluate crop productivity in Ghana. Dzotsi et al. (2010) used the DSSAT model to successfully simulate the effect of phosphorus limitations on maize growth and yield. Nurudeen (2011) simulated maize growth and yield response to NPK fertilizer application on a benchmark soil in the savanna AEZ and reported that maize grain yield was affected by different rates of fertilizers. He reported that 160-90-90 (NPK) had the highest grain yield. He attributed this result to the high rates of NPK fertilizer. Tuong (1999) and Rockström et al. (2002) observed that nutrient application effect was linear between maize yield and water productivity per unit water transpired. Although the model showed significant effect on maize yield and growth, Nurudeen (2011) recommended that sensitivity to N fertilizer rates should be improved in order to make predictions for treatments without N fertilizer more accurate.

Soler et al. (2007) used DSSAT to successfully predict maize yields under different management practices. They also indicated that DSSAT simulation could be used to select the best option for sustainable production of maize and other crops.

Fosu et al. (2012) simulated the growth, development and yield of Obatanpa maize at Nyankpala in the northern savanna agro-ecological zone with DSSAT. They found out that the model accurately simulated maize grain yield up to 90 kg ha⁻¹ N but failed to accurately predict maize grain yield when N was applied at 120 kg ha⁻¹. They concluded that excessive water stress

induced N application rate $\leq 90 \text{ kg ha}^{-1}$ on silty clay loam soils (Gleyi-Ferric Luvisols) of the Guinea Savanna agro-ecological zone of Ghana. MacCarthy et al. (2012) evaluated the response of maize to N fertilization under two field experiments and reported that maize grain and biomass yields at Prediction Index of Agreement (PIA) between 0.64 and 0.95 yielded better results with higher rates of N fertilization and lesser water stress conditions. They also reported that the sensitivity of selected soil parameters to grain yield was more when no N fertilizer was applied.

Naab et al. (2004) and Musunguzi et al. (2014) reported that DSSAT presents the flexibility of simulating complex heterogeneous farming systems in the tropics and cropping systems. The DSSAT model has been satisfactorily calibrated, evaluated and hence, can be used to aid decision making in respect of farm management options (Naab et al., 2004). In effect, crop models offer the possibility to compare the productive advantages of different soils for maize production in Ghana.

2.6 Multi-Criteria Analysis (MCA)

The decision to intensify crop production at a given location should not take in consideration only soil, weather and management factors but also economic factors. Combining economic parameters with edaphic, management, and weather factors did not initially receive sufficient attention. Most decisions were either based on biophysical determination or economic considerations, but not both. Conceivably, the inclusion of economic parameters will require appropriate tools.

The Multi-Criteria Analysis (MCA) provides tools for complex problems solving (Mysiak et al., 2005) by considering multiple criteria in decision-making environments. By using MCA

tools, confusion could arise if logical, well-structured decision-making processes are not followed (Janssen, 2001). Hence, there are differences in the quality of MCA alternatives (Janssen, 2001; Wolfslehner et al., 2005). Every decision is made within a decision environment. Thus, MCA provides techniques for comparing and ranking different outcomes, even though a variety of indicators are used (Macoun and Prabhu, 1999; Temponi et al., 1999; Figueira et al., 2005). Pearman et al. (1989) reported that the objectives of using MCA are usually conflicting and in most cases, different groups of decision-makers are involved. To facilitate this type of analysis, a family of tools referred to as multi-criteria decision-making methods were developed, thus, have a formalized method to assist decision-making processes (Pearman et al., 1989). Bell et al. (2003) indicated that the formalized method was particularly applicable to cases where a single-criterion approach (such as cost-benefit analysis) falls short, especially where significant environmental and social impacts could not be assigned monetary values. Multi-criteria analysis allows decision users to include full range of social, environmental, technical, economic and financial criteria (Pearman et al., 1989; Jones et al., 1990; Hämäläinen et al., 1992).

2.6.1 Application of MCA in Agriculture

Although agricultural decision-making may be considered as complex and a dynamic process (Pearman et al., 1989; Jones et al., 1990; Hämäläinen et al., 1992), a set of tools that presents both benefits and limitations to users are important. Researchers such as Gasparatos and Scolobig (2012) have suggested MCA as an appropriate tool to address sustainability in agriculture, though they did not provide an empirical application. They emphasized the need for methods that are able to simultaneously deal with all impacts of agriculture on the

environment and the economy. Store and Kangas (2001) and Secretariat (2008) were able to analyse and predict spatial functions, conduct criterion standardization, weighting and combining of indicators in habitat suitability evaluation. In agricultural regions of Greece, Koutroumanidis et al. (2002) compared and ranked crop productivity with MCA tools. Dooley et al. (2009) reported that MCA may be as effective as more complex models, and can deliver many of the benefits particularly where time is limited. In achieving optimum utilization of the available land resources for rice production in the Mwea region of Kenya, Kihoro et al. (2013) also adopted MCA tools to identify the best combination of factors that suited rice cultivation.

2.6.2 Use of MCA for Agricultural Management in Ghana

The use of MCA for soil and agriculture management in Ghana is increasing. Adiku et al. (1998) used stochastic dominance and MCA tools to assess the performance of maize and cowpea in sole and intercropping farm systems. They concluded that for sustainable productivity, the total crop residue and the quantity of nitrate-nitrogen returned to the soil by crop residue after harvest, and aerial cover provided by plants should be assessed. Furthermore, Rose and Adiku (2001) employed MCA to compare the productivity of sole maize and maize-cowpea inter-crop in some northern zones of Ghana. Dowuona et al. (1999) investigated and assessed three landuse systems in the sub-humid zone with MCA tools for landuse planning. The ultimate goal is to integrate MCA methodology into a wider frame of cost-benefit analysis (CBA) so as to support policy and decision-making, especially in the context of sustainable development.

The use of MCA in this study is therefore an appropriate tool to assess the overall suitability of different soils for intensive maize production.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Study Area

3.1.1 Location

The study areas are in the Brong Ahafo and the Northern Regions of Ghana (Figure 3.1). They are located in the forest-savanna transition and guinea savanna agro-ecological zones respectively.

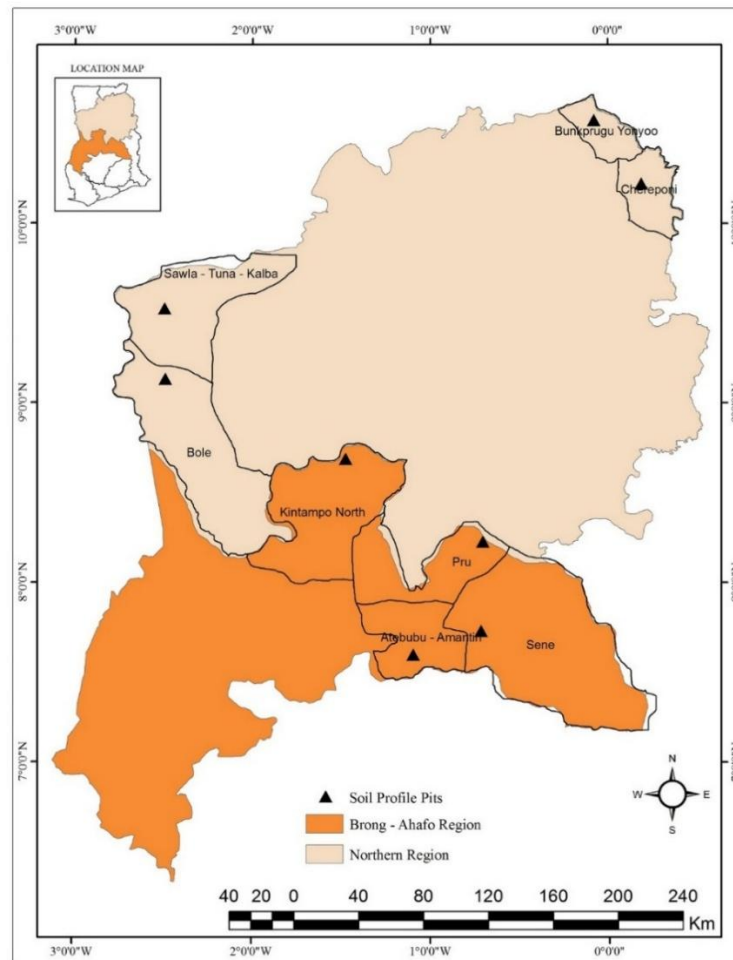


Figure 3.1. Location of Study Areas

The communities in the study areas are shown in Table 3.1. The GPS coordinates (Table 19, appendix 2) were taken at each site to aid the development of maps.

Table 3.1. Districts and Communities of Study Areas.

Region	Districts	Communities
Brong Ahafo	Pru	Kwayasi – Yeji
	Sene	Shafa – Wiase Zongo
	Atebubu – Amantin	Lailai
	Kintampo North	Alhassan Kura
Northern Region	Bunkpurugu – Yunyoo	Nannik
	Chereponi	Famisa
	Bole	Gbogdaa
	Sawla-Tuna-Kalba	Nahari

3.1.2 Physiography of the Study Areas

The study area falls within the guinea savanna and forest – savanna transition agro-ecological zones of Ghana (Figure 3.2).

3.1.2.1 Guinea Savanna

The climatic conditions of the Guinea Savanna zone is characterized by well-defined wet and dry seasons of about equal durations with mean annual rainfall of between 900 – 1100 mm (Ghana Meteorological Service, 2010) (Figure 3.2).

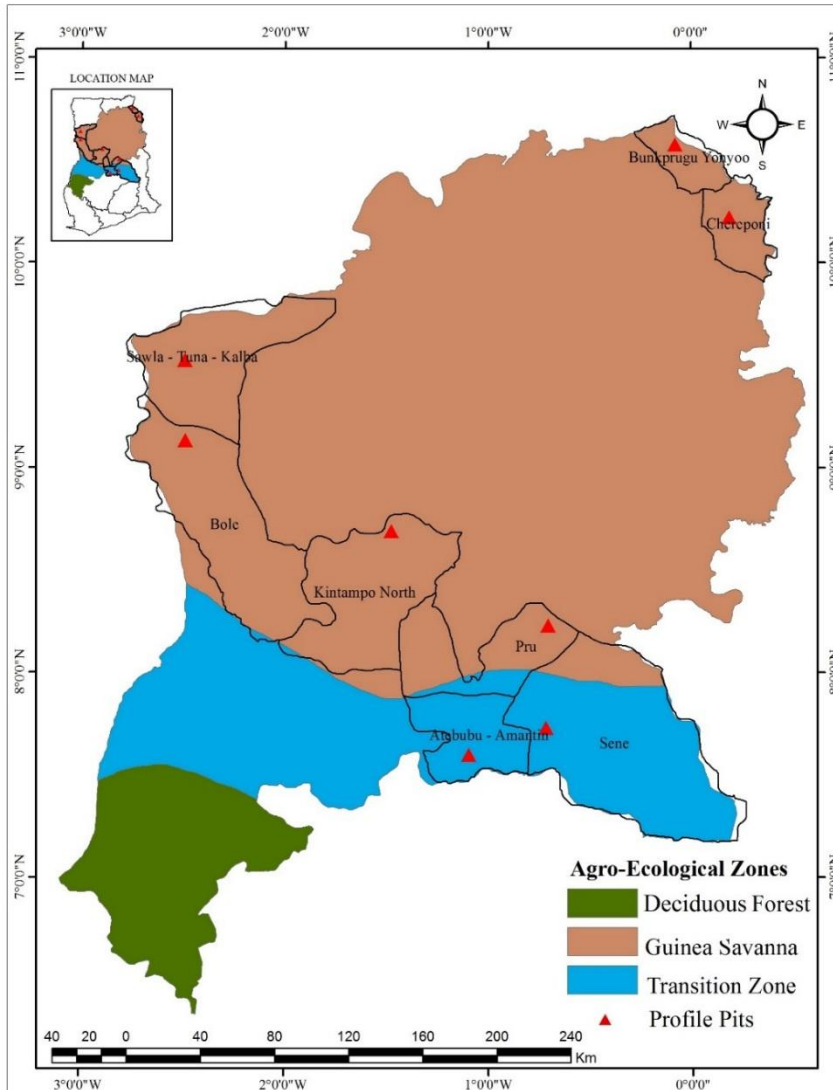


Figure 3.2. Agro Ecological Zones (AEZ) Showing Study Sites

Monthly rainfalls increase gradually from March until a maximum is reached in August or September. Changes occur between successive rainy seasons regarding onset, duration and amounts of precipitation making predictions very difficult. The mean monthly temperatures are high throughout the year ranging from 25 °C to more than 33 °C as shown in Figure 3.3.

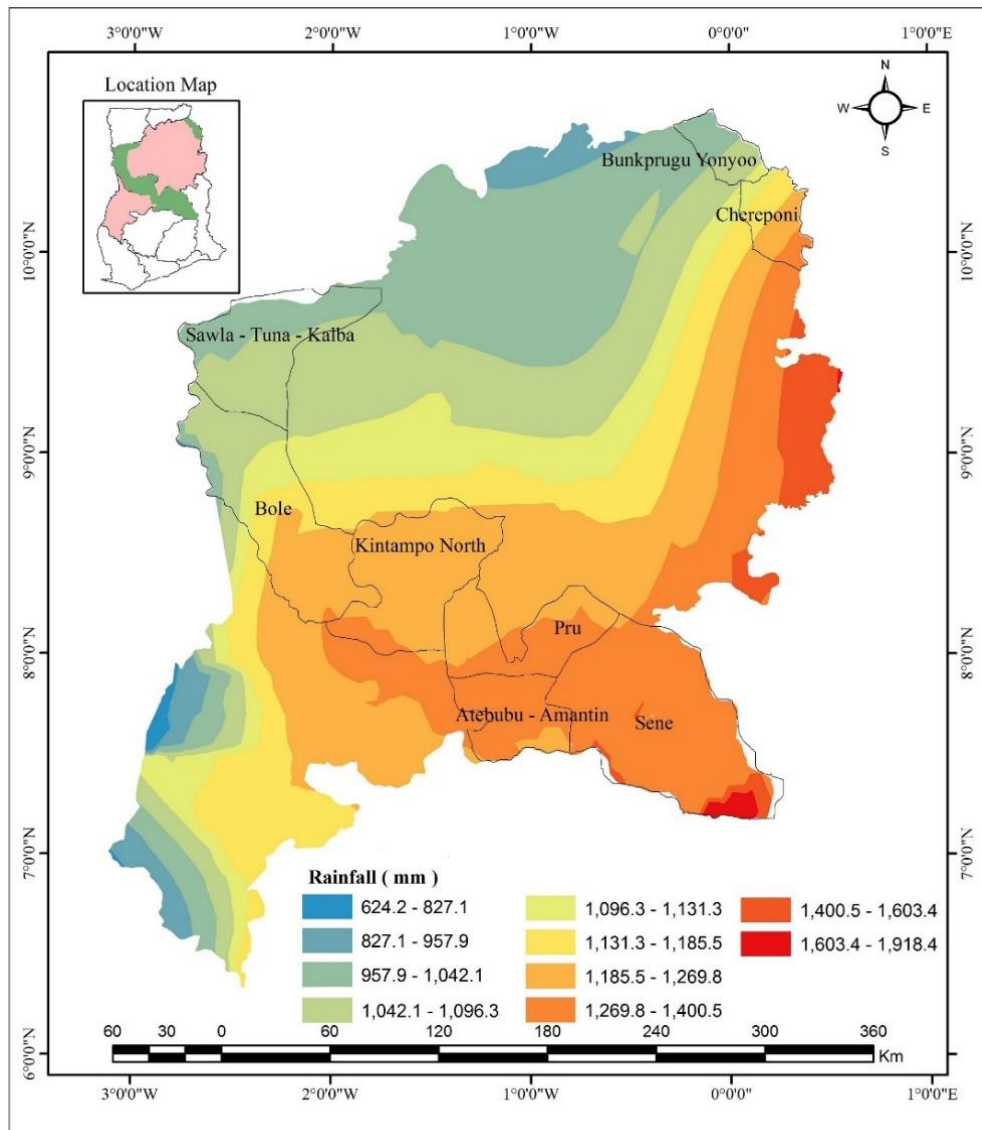


Figure 3.3. Mean Monthly Rainfall Distribution (1975 - 2005) at the Study Areas.

Relative humidity ranges from 75% in the rainy season to 35% in the dry and hot periods. The vegetation of the study area is predominately tall grasses with scattered trees and shrubs.

3.1.2.2 Forest – Savanna Transitional Zone

The rainfall pattern in the Forest-Savanna Transition Zone (Figure 3.2) is characterized by a major rainy season starting from April through May and June to the second week of July. Within

this period, over 66% of the total annual rainfall may be recorded. The minor rainy season occurs from August to October and sometimes to November, followed by a long dry season from December to the end of March or early April. The total annual rainfall varies from 1100 mm to 1400 mm as shown in Figure 3.3. Temperatures in the zone range from 17 °C to 33 °C (Figure 3.4) with the lowest being recorded in August and the hottest in December to February (Ghana Meteorological Service, 2010).

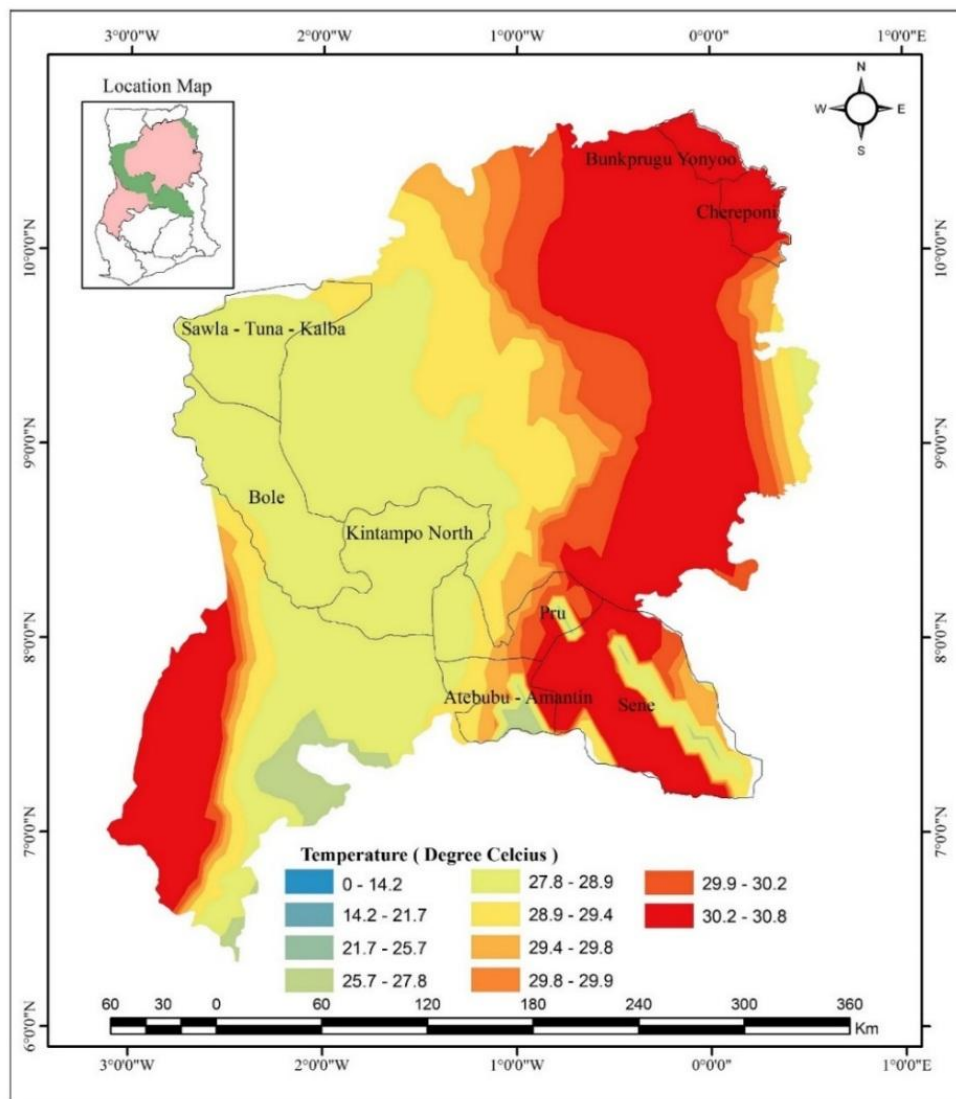


Figure 3.4. Mean monthly temperature distribution (1975 - 2005) at the study areas.

3.1.3 Relief and Drainage

The study sites are predominantly nearly level to gentle slope with a gradient of about 0.5 – 5% (Figure 1 to 8, see appendix 1). The wide river valleys and depressions are almost flat with slopes of about 1 – 3%. There are also isolated hills and high lands within the study area. There are a number of major and minor rivers all over the study areas which get flooded during the rainy season.

3.1.4 Geology

The underlying geology of the study area consists of sedimentary rocks, mainly sandstone, clay shale and mudstone of early carboniferous age (Junner, 1946). The geological formations over which the soils have developed include coarse and fine grained voltaian and/or feldspathic sandstones, granite, voltaian clay, shales and mudstone, mainly colluvial and alluvial deposits. Table 3.2 shows the study areas and their associated geological formations.

3.1.5 Characteristics of Soils in the Study Areas

Generally, the soils within the interior savanna and forest savanna transitional zones are shallow (15 – 30 cm) but some few deep soils (100 – 150 cm) can also be found. The soils of the upper summits and middle slopes are well to moderately well drained, red and yellowish brown, medium to light textured depending on the parent material from which the soils were developed. They may contain very few (1%) to many (over 15%) ironstone nodules or concretions at various depths.

The soils on the lower and middle slopes were developed over colluvio-alluvial deposits in large depressions and valley bottoms showing pronounced hydromorphic properties (Thompson et

al., 1997). They are moderately shallow to deep and show various degrees of erosion. The soils used for this study are described below (Table 3.2).

Table 3.2. Study Sites with Associated Geological Formations

District	Community	Geology	Dominant Soil Series
Bunkprugu – Yunyoo	Nannik	Sandstone	Mimi
Atebubu – Amantin	Lilai	Sandstone (Feldspathic)	Ejura
Pru	Kwayasi – Yeji	Clay Shale & Mudstone	Wenchi
Sawla – Tuna – Kalba	Nahari	Granite	Varempere
Bole	Gbogdaa	Granite	Kupela
Kintampo North	Alhassan Kura	Clay Shale & Mudstone	Lima
Chereponi	Famisa	Clay Shale & Mudstone	Kpelesawgu
Sene	Shafa – Wiase Zongo	Sandstone	Damongo

3.1.5.1 Ejura Series

The Ejura series is the dominant series in the Lailai community in the Atebubu – Amantin district. The Ejura series has been classified as Haplic Lixisol (Agyili, 2003). The soil is well drained, reddish brown to red in colour. It is developed in-situ on summits and upper slopes from fine grain voltaian sandstone. The profile consists of 20-25 cm dusky red, porous, fine sandy loam topsoil which grades into 25-125 cm of red, sandy clay loam, weak to moderate fine subangular blocky, friable, soft, slightly sticky and slightly plastic subsoil. Shown below in Figure 3.5 shows the location of Ejura series (the Ejura – Amantin/Denteso association).

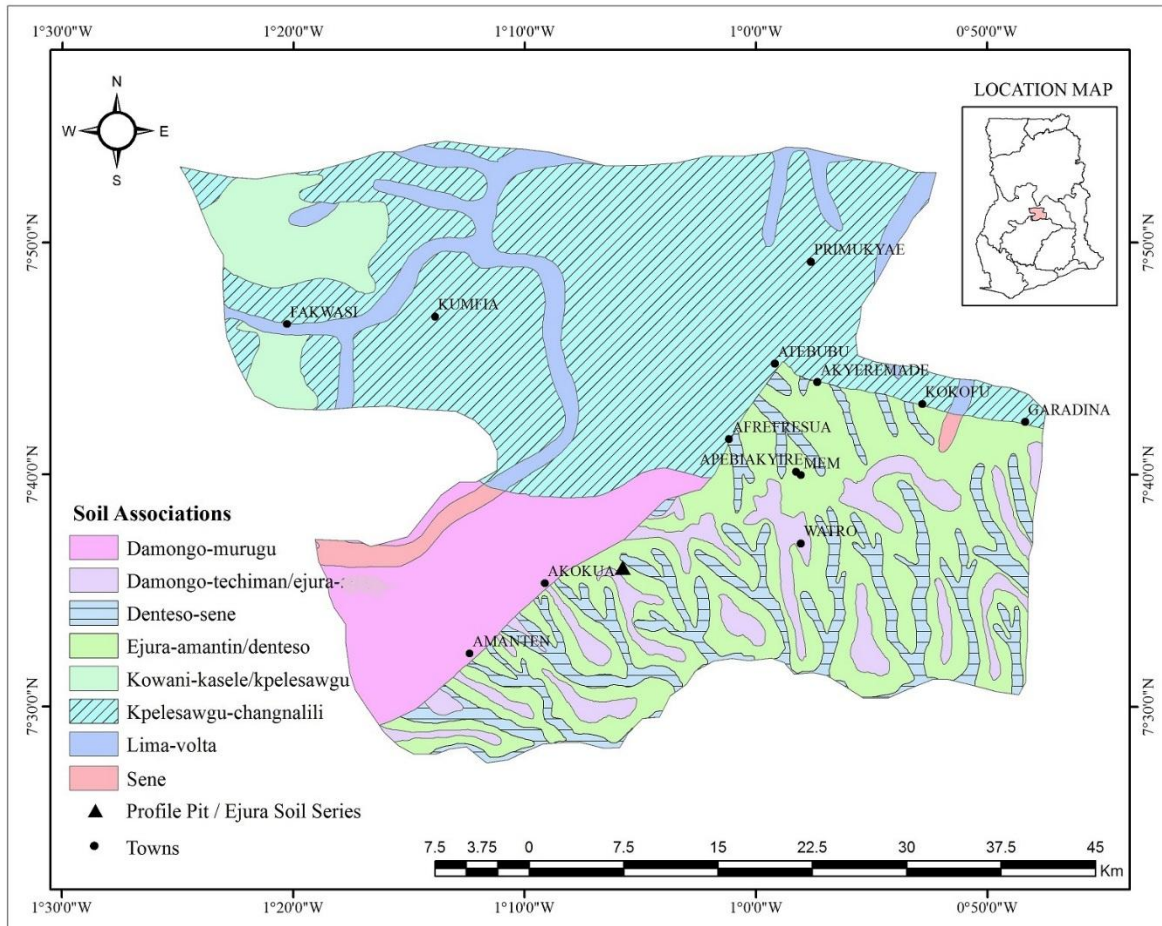


Figure 3.5. Soil map showing Ejura – Amantin/Denteso Association and other soils

3.1.5.2 Lima Series

The Lima series is the dominant soil found in the Alhassan Kura community in the Kintampo North district (Figure 3.6). Agyili (2003) classified Lima series as Eutric Gleysol. The soil is poorly drained, developed over colluvio-alluvial deposits of clay shale and mudstone. It occurs on the lower slopes of very gentle slopes (about 1-2%). It is very deep (over 150 cm), pinkish gray and strongly mottled. They have sandy loam to silty clay texture with calcium carbonate nodules in the depth of the soil profile. The soil is grayish brown and sandy loam in texture and has weak to moderate medium granular structure. The soil is friable, soft, slightly sticky, slightly plastic in the topsoil over very thick (20 – 125 cm), clay loam, pale brown and grayish brown mottled strong brown structureless subsoil. The subsoil contains few ironstone and manganese concretions.

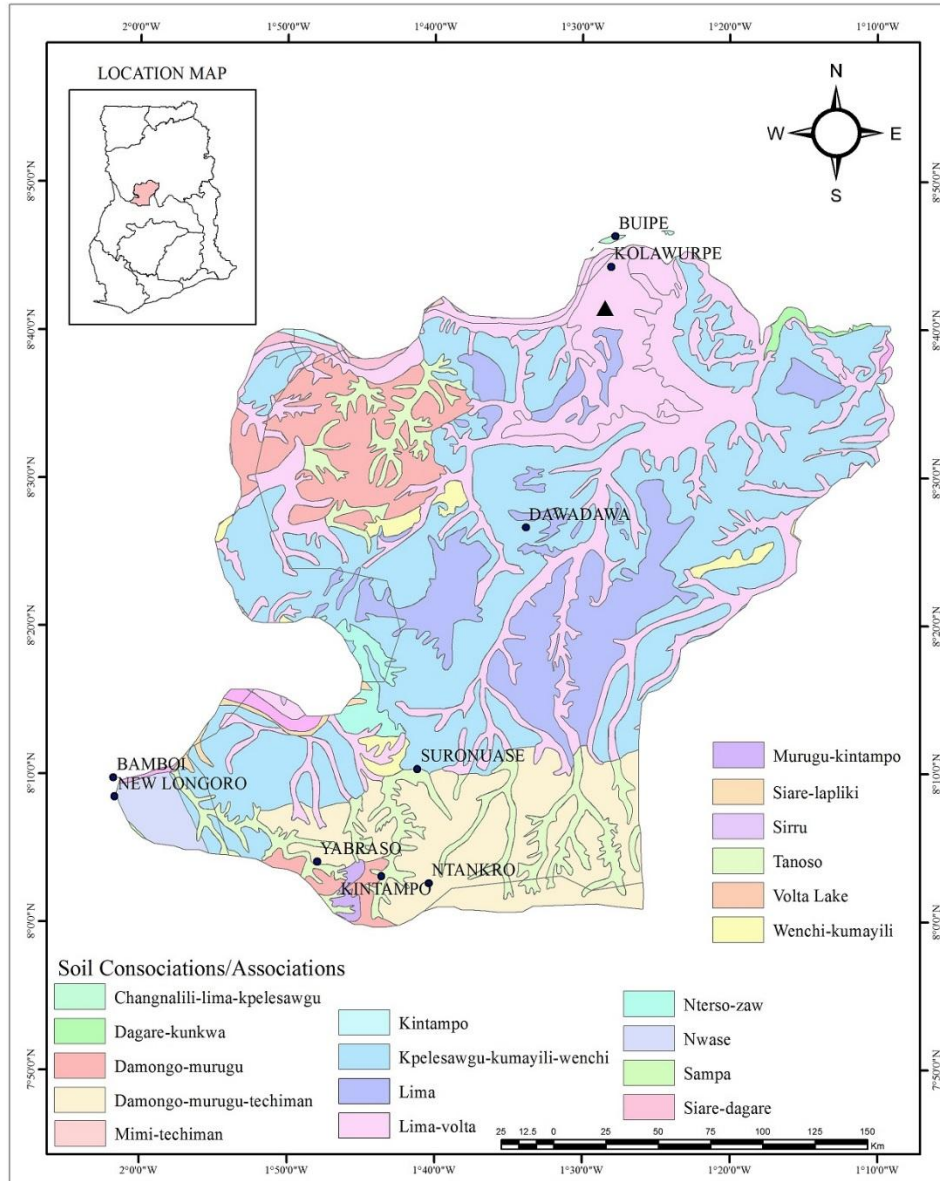


Figure 3.6. Soil map showing Lima Series and other soils

3.1.5.3 Mimi Series

Mimi series is one of the dominant soils at Nanniik in the Bunkprugu – Yunyoo district (Figure 3.7). Adu (1995) classified Mimi series as Haplic Lixisol. Mimi series is deep, dark brown, well drained, red, friable and developed in-situ from voltaian sandstone. Its topsoil (18 – 25 cm) is friable, sandy loam and weak with fine granular structure over thick (25 – 150 cm) dusky red,

sandy clay loam, weak to medium subangular blocky, slightly sticky, non plastic and friable non-gravelly subsoil.

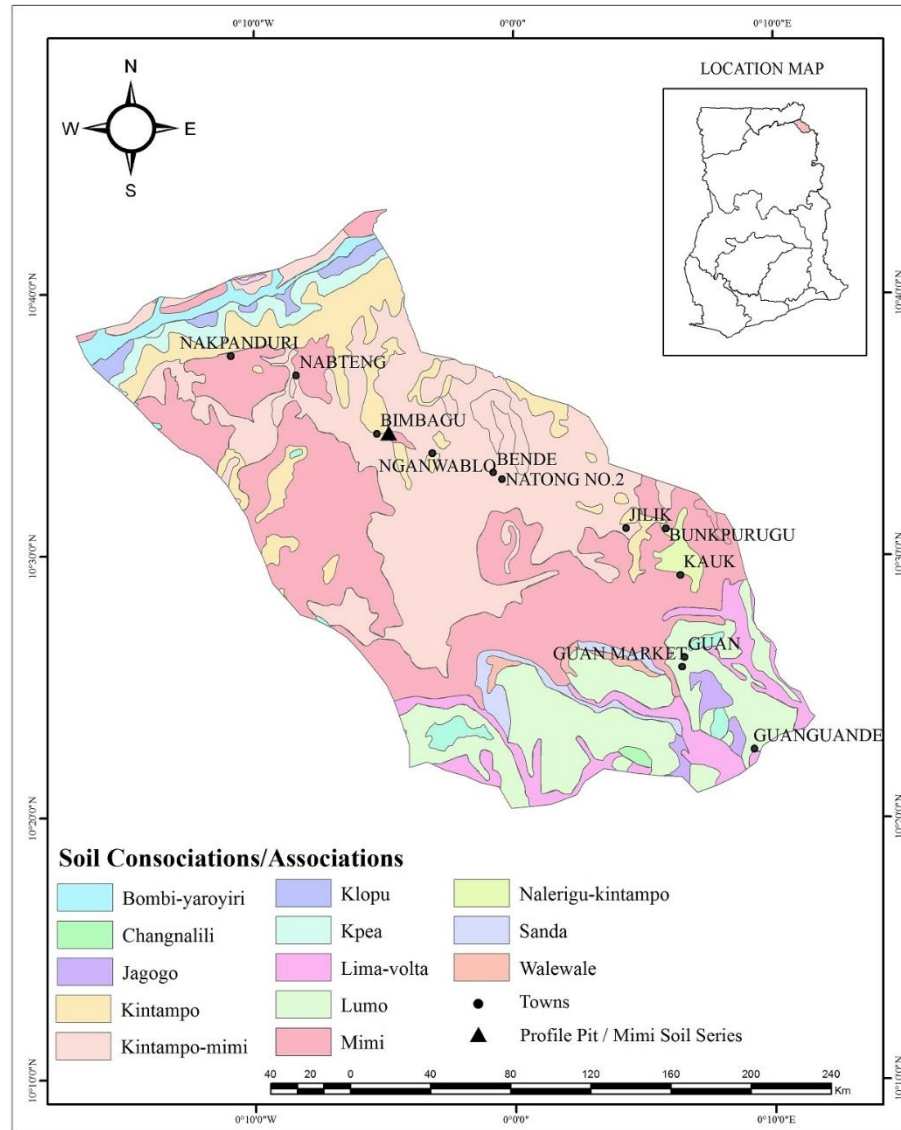


Figure 3.7. Soil map showing Mimi Series and other soils

3.1.5.4 Wenchi Series

The Wenchi series has been found to dominate the landscapes of the Kwayasi – Yeji community in the Pru district. It is a very shallow soil (15 – 30cm) with massive ironpan at less than 30 cm

from the soil surface or may be exposed at the surface (Agyili, 2003). It was classified as Ferric Dystric Leptosol (Agyili, 2003). Figure 3.8 shows the Wenchi series (Kpelesawgu – Kumayili – Wenchi association).

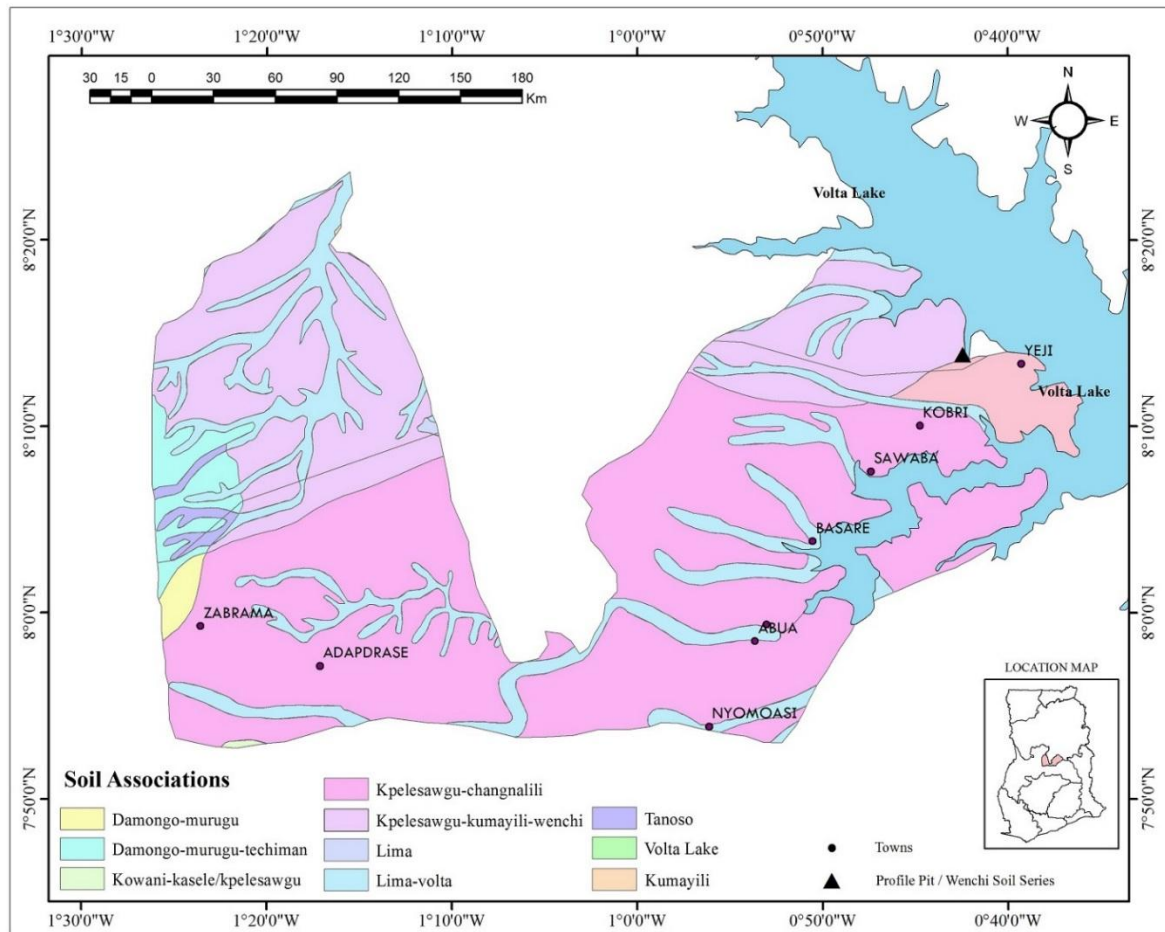


Figure 3.8. Soil map showing Wenchi Series and other soils

3.1.5.5 Kpelesawgu Series

The Kpelesawgu series is the dominant soil series in the Famisa community of the Chereponi district (Figure 3.9). This soil was classified as Eutric Plinthosol by Adu (1995). It is deep (about 195 cm), dark greyish, sandy loam with frequent to abundant ironstone nodules on the lower

slope of the catena. It is also underlain by massive ironpan which makes the soil prone to flooding in the rainy season (Adu, 1995).

3.1.5.6 Kupela Series

The Kupela series is one of the major soils of the Gbogdaa community of the Bole district (Figure 3.10). Adu and Asiamah (2003), classified Kupela series as Eutric Gleysol. The soil is moderately deep (60 – 100 cm), poorly drained, dark brown to gray, strongly mottled, strong brown and yellowish brown in colour with sandy clay texture. The topsoil of Kupela series is thick (25 cm) gray in colour with yellowish brown mottles.

The topsoil is sandy clay with a moderate medium granular structure. It has rusty root channels over thick (25 -125 cm) subsoil which is sandy clay loam to clay in texture. The structure of the subsoil is moderately medium subangular blocky to massive. The consistency is sticky plastic. The subsoils are very firm with common to many ironstone nodules and quartz gravels and stones. Calcium carbonates concretions are observed between 100 and 125 cm.

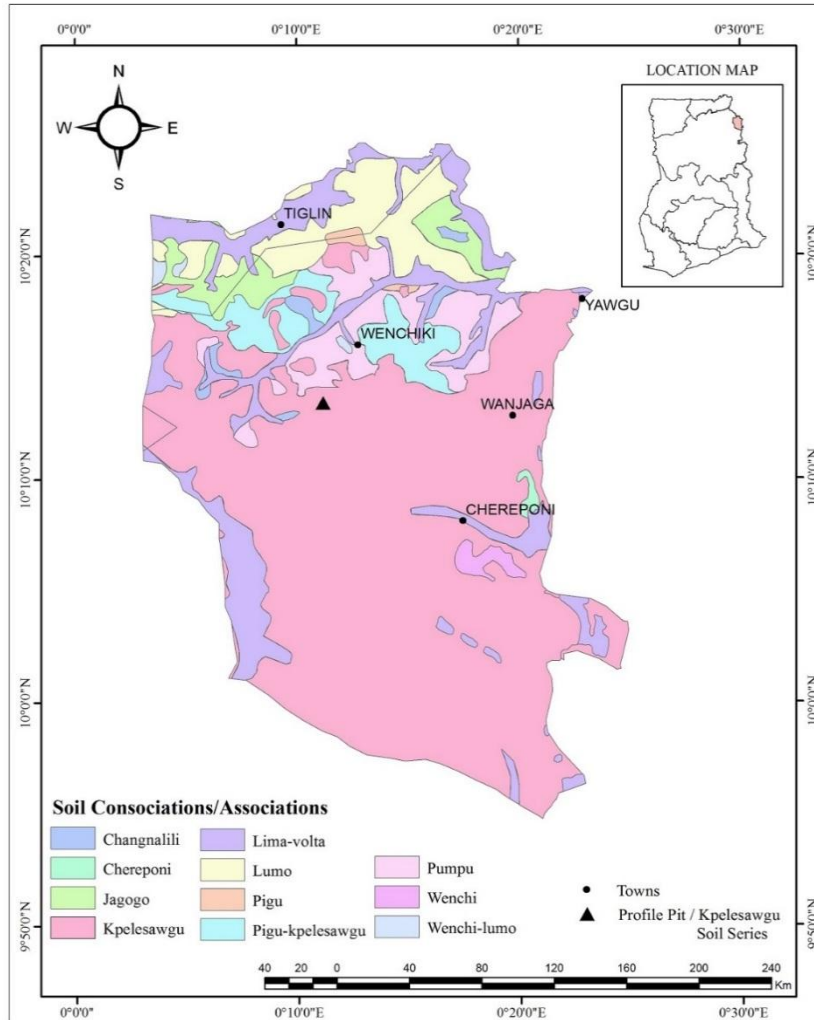


Figure 3.9. Soil map showing Kpelesawgu Series and other soils

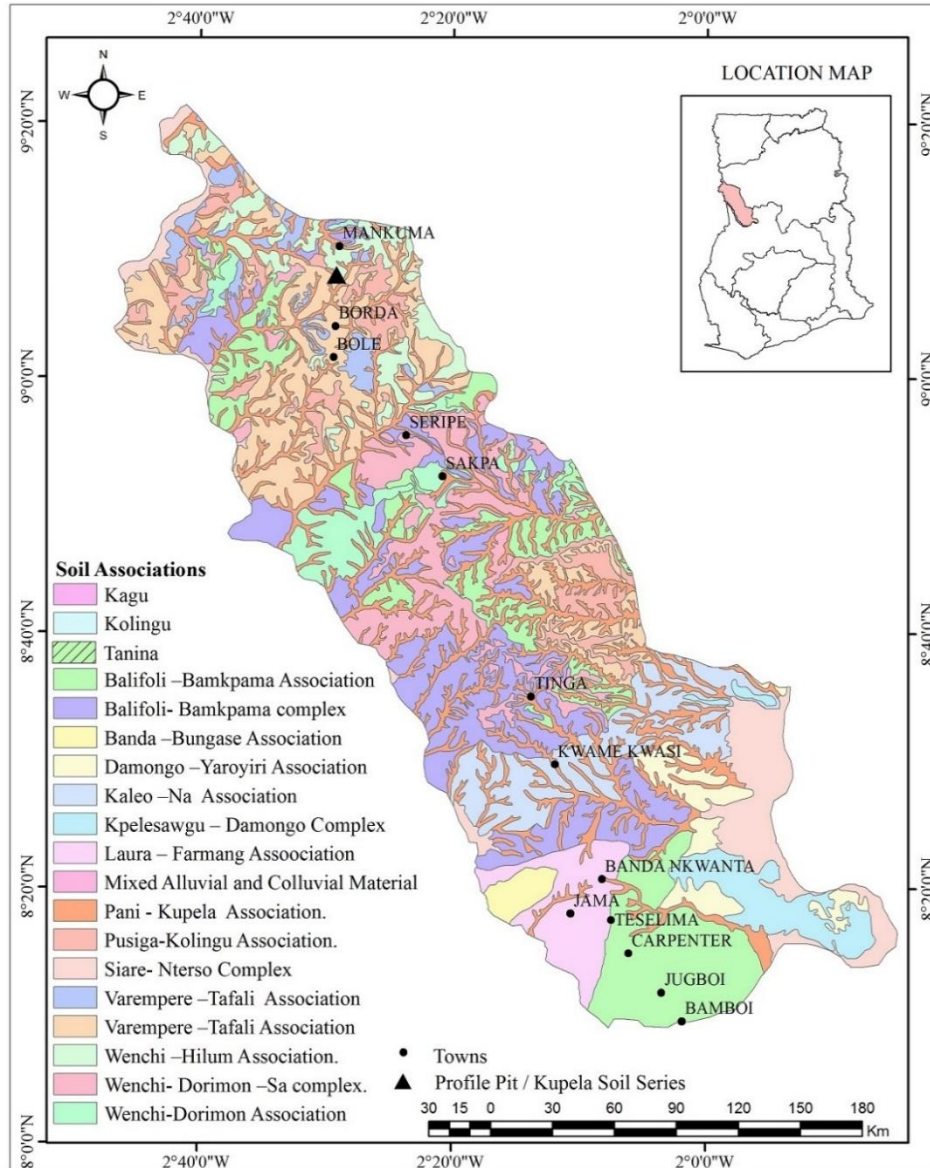


Figure 3.10. Soil map showing Pani – Kupela association and other soils

3.1.5.7 Varemper Series

The Varemper series is the dominant soil in the Nahari community of the Sawla – Tuna – Kalba district (Figure 3.11). Adu and Asiamah (2003) classified Varemper series as Ferric Luvisol and reported that the soil is very deep (>150 cm), sedentary and developed from granite. The soil is found on summits and upper slopes of the catena.

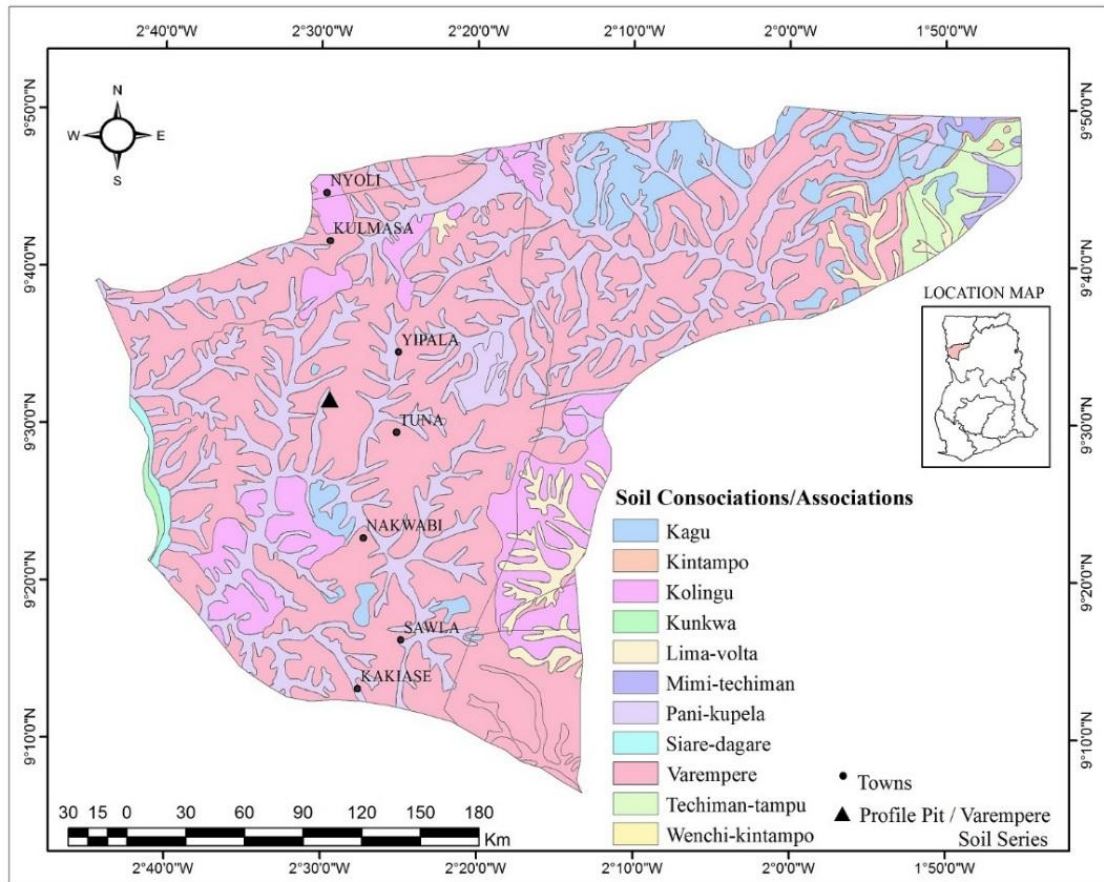


Figure 3.11. Soil map showing Varempere – Tafali association

The soil is moderately well drained, brownish yellow to yellowish red in colour with sandy clay loam to sandy clay texture found on gentle slopes. The top soil (15 – 25 cm) is dark brown, loamy sand, weak fine granular, non-sticky non-plastic overlying the thick (25 – 155 cm) brownish yellow to yellowish red subsoil. The subsoil has a moderate to strong medium subangular blocky structure, faintly mottled, sandy clay to gritty clay texture, slightly sticky and slightly plastic in consistence. At 155 – 175 cm, it has a firm structure with few to common iron, manganese dioxide nodules and quartz stones and gravels. In the last horizon, it has a massive structure.

3.1.5.8 Damongo Series

The Damongo series dominates the landscape of Shafa Wiase Zongo Community of the Sene East District (Figure 3.12). Damongo series from the Damongo – Murugu association was classified as a Dystric Nitisol (Agyili, 2003). Agyili (2003), reported that Damongo series is thick, well drained, with about 2-5% slope with signs of slight soil erosion. It has a brownish black loam sand topsoil with a dark reddish brown sandy clay loam subsoil. It is medium textured, has good tilth and easily workable with machines. Agyili (2003) concluded that they are the best soils in the sandstones of the savanna.

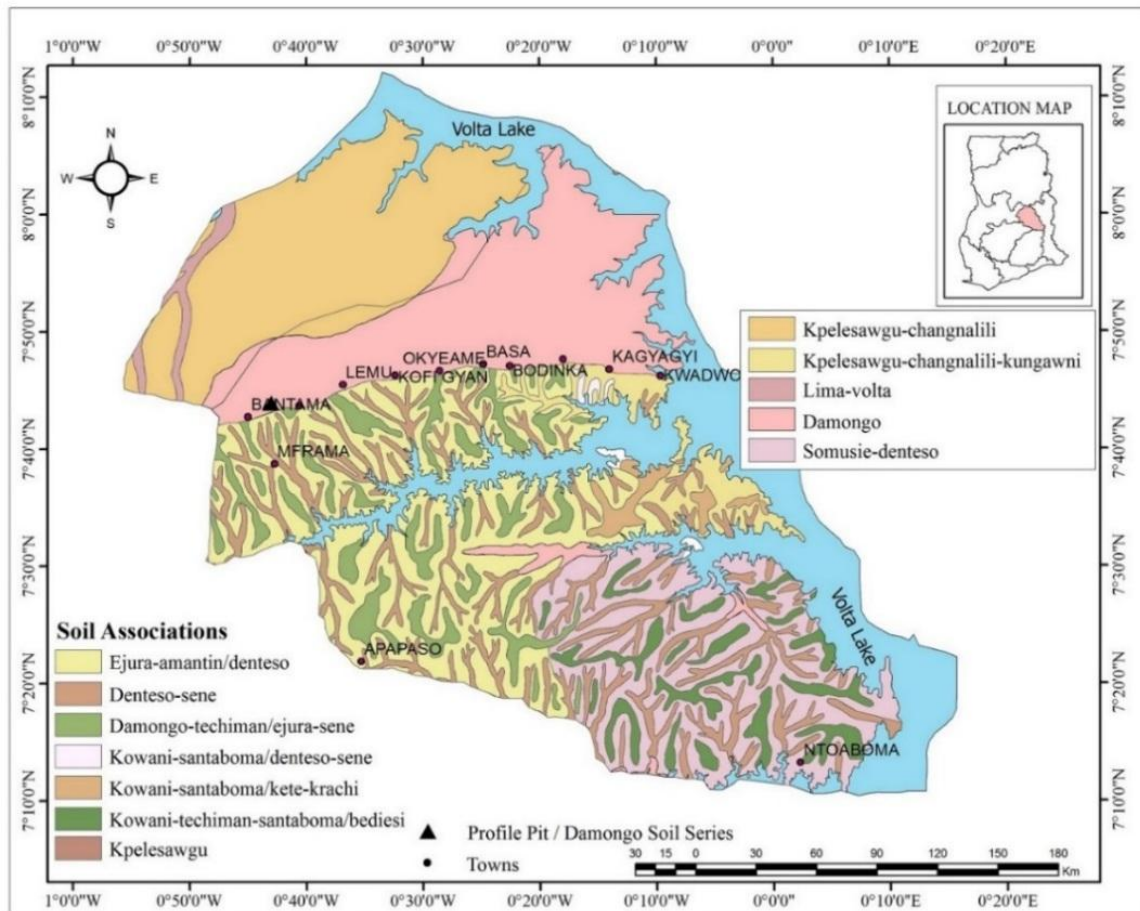


Figure 3.12. Soil map showing Damongo – Murugu association

3.1.6 Current Landuse and Management Practices Adopted by Farmers

Paschal et al. (2013) reported that farmers in the study areas have crop production, poultry and livestock as their main sources of livelihood. Food crops such as maize, millet, sorghum, cowpea and yam are the main crops cultivated on the agricultural lands in the Northern region (Figure 3.13).

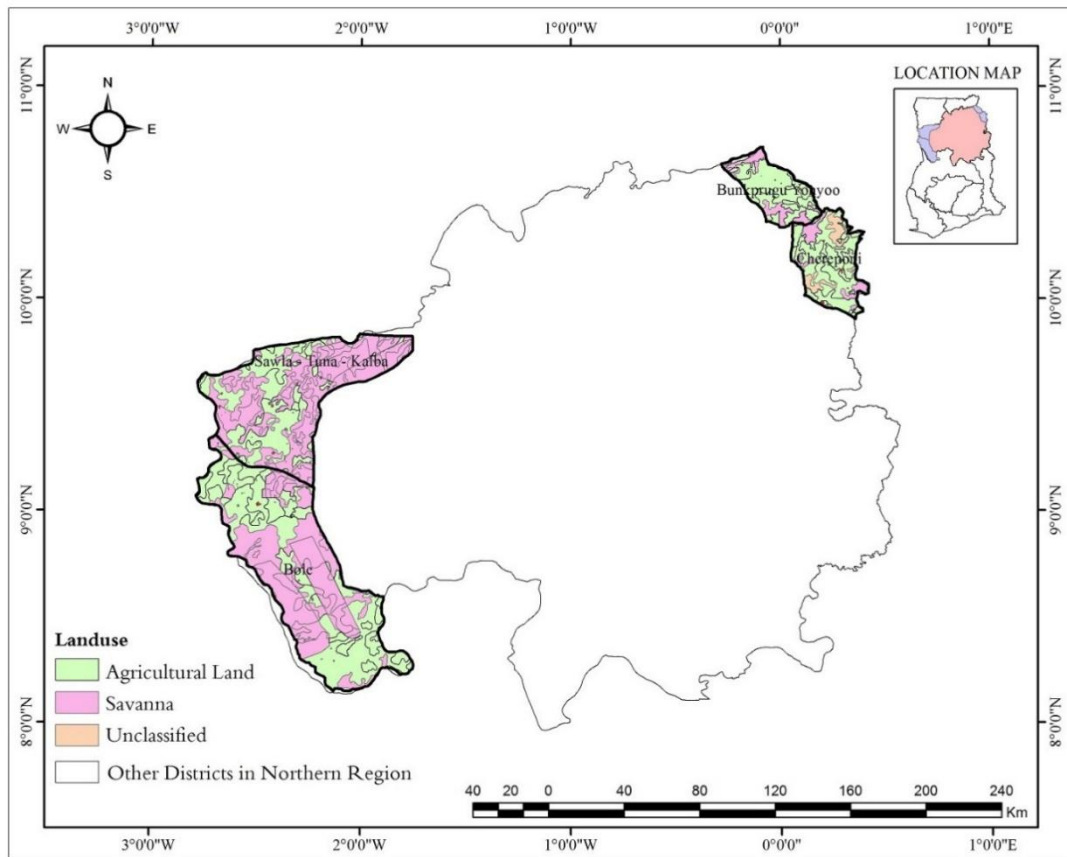


Figure 3.13. Landuse in the northern region

In the Brong Ahafo Region, maize, cowpea and yam are the food crops mainly cultivated (Figure 3.14). Farm sizes range from about 0.2 to 2 ha and about 1 to 10 ha in the Northern and Brong Ahafo regions respectively. Soil management is key to the continual capability of the soils to function productively. Only few farmers were observed to be implementing some soil

management interventions. Although cropping systems such as monocropping and intercropping were common (Paschal et al., 2013), it was realized that crop residue incorporation into soil was hardly practiced as a soil management intervention by farmers in the Northern region.

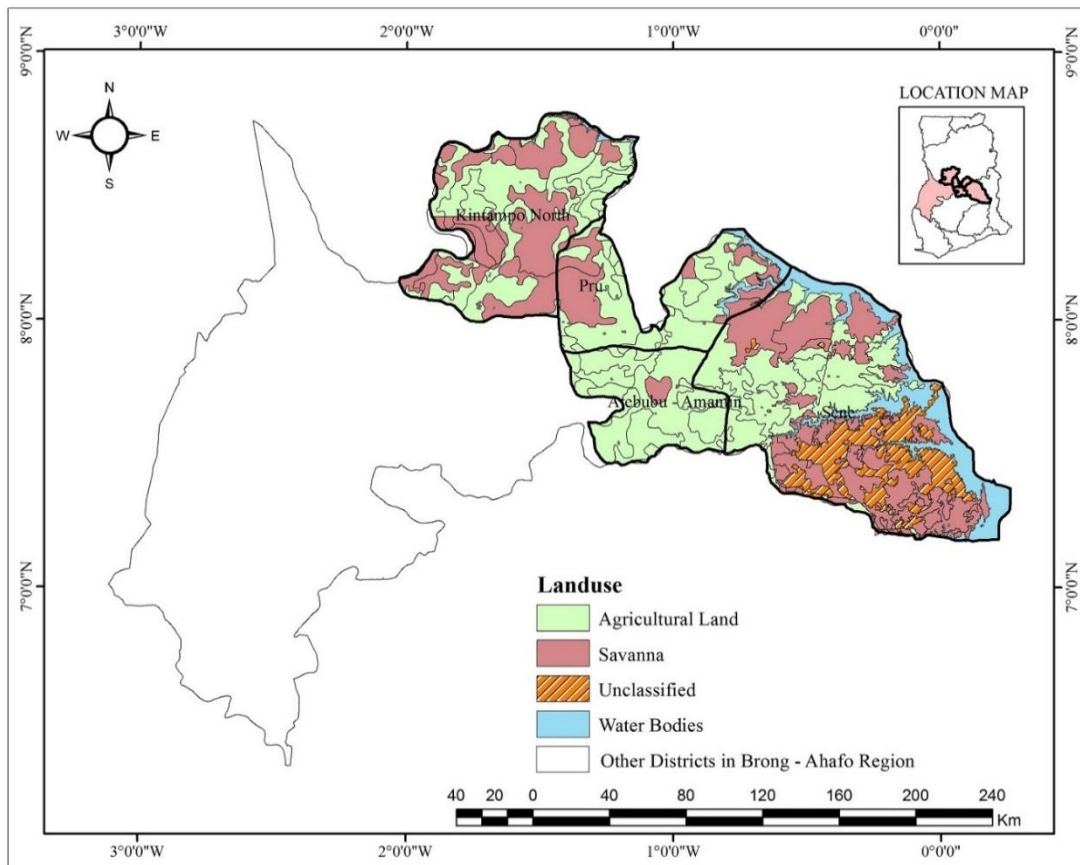


Figure 3.14. Landuse in the Brong Ahafo region

On the other hand, in the Brong Ahafo region, incorporation of crop residue into the soil was fairly commonly practiced. The majority of the farmers graze their livestock on crop residues especially in the Northern region. Furthermore, the farmers explained that crop residues left on the field easily cause fire so they prefer to allow animals to graze on their fields after harvesting. Therefore, farmers who had adopted retention of crop residue to improve their soils had fire

belts around their farms. Other farmers who kept livestock, brought manure to their farms to improve the fertility status of the soil. Some farmers also used mineral fertilizers.

The farmers cultivated cowpea in every third year. This practice was adopted because of observed improvement in maize production after every other year of cowpea cultivation. This practice was adopted by about 80% of the farmers in the Northern and Brong Ahafo regions. Also, ridging and mounding were fairly adopted as ways of curbing soil erosion and as a means of conserving soil water.

3.2 Data Collection

This study was categorized into three stages; (1) pre-fieldwork, (2) field data collection and (3) post-field data analysis. Data was collected during the end of the minor rainy season of 2013 at a time that the crops were either harvested or about to be to be harvested.

The first type of information gathered was socio-economic in character. Focused group discussions and other questionnaires were used to document the farmer's current cropping and soil conservation practices, labour use on farms, distance from markets, among others. Second, soils were sampled from profile pits dug at the various District communities and brought to the laboratory for analysis. In addition, secondary data sources were also used to help identify the major soil series that were dominant on farmer's fields. Third, weather data covering a period of 30 years (1975 to 2005) were obtained for the various locations from the Ghana Meteorological Agency.

3.2.1 Soil Profile Data Acquisition: Sampling and Description

In the pre-field data assessment, published data (in this case soil profile information) were obtained from the CSIR-Soil Research Institute. This was for the purpose of identifying the most extensive soil series in each study area to be examined. Cline (1944) reported that soils vary vertically and horizontally, hence there was the need to carefully observe, confirm and describe the soil series under investigation thoroughly. With the reference soil data, soil series were observed in the field on traverses of about a 50 – 100 m (depending on the locality and topography of the area). These traverses were established along catenas to identify variability in the soils of the study areas and also identify benchmark soil series. Soils were observed at approximately 25 m intervals along the traverses by means of augering and/or chisel holes dug to about 30 cm in diameter and 40 - 50 cm deep.

During the survey, soils were described along the traverses using morphological characteristics such as effective depth, colour, texture, mottles and coarse fragments. Other site characteristics considered were the physiographic position, slope, drainage, parent material and the prevailing land use of the site. Soil profiles were further examined by means of a soil profile pit. This was dug using chisel, pickaxe and shovel. The profiles measured 200 cm by 100 cm to a maximum depth of 150 cm or to an impenetrable layer or water table (FAO, 2006). Soil series name, location of the soil, slope, elevation, geographic position system (GPS) coordinates, drainage condition, vegetation, landuse, etc. were recorded. Prior to description of profiles, pits were cleaned and horizons marked as shown in Figure 3.15 (FAO, 2006; Lindbo et al., 2008). The soil horizons were described according to FAO (2006).

To avoid contamination of soil samples taken from horizons, sampling was done from the bottom to the top of each profile.

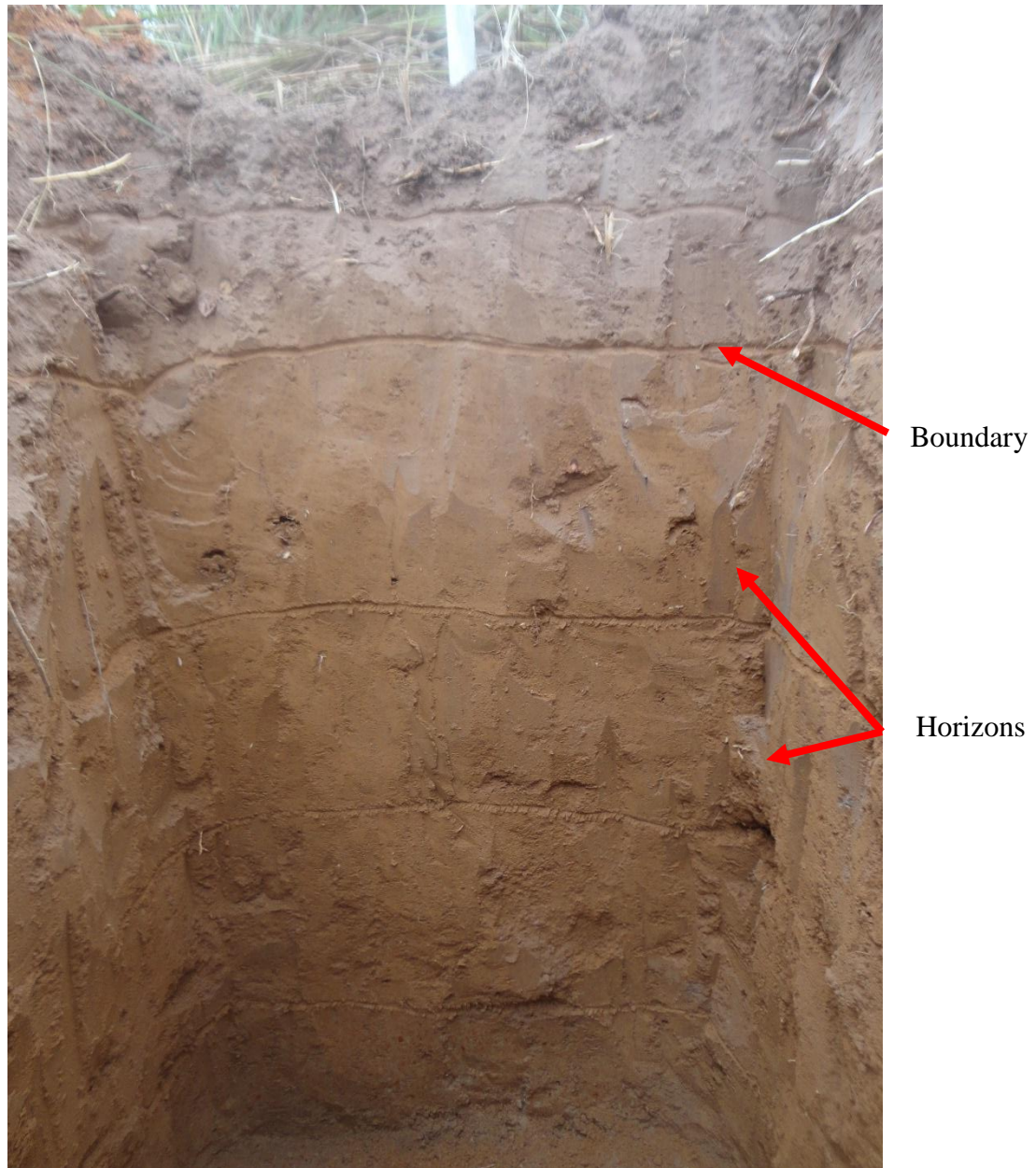


Figure 3.15. A Soil Profile Showing Horizons

Each soil horizon was described as follows;

1. **Soil depth:** a measuring tape was used to measure the thickness of each soil horizon.
2. **Soil consistence:** the soil samples were examined for their stickiness and plasticity, resistance to rapture and penetration under wet, moist or dry condition.

3. **Soil colour and mottling:** peds from each horizon were matched with colours in the colour chart and colours determined (Colour, 1991). Mottles, if present, were also described using the Munsell colour chart. Records taken on mottles included quantity, size and contrast.
4. **Soil texture:** the feel method was used to determine texture of the soil samples in the field.
5. **Soil Structure:** the structure of the soil samples were determined under class, grade and size. The grade was used to determine the degree of aggregation, the class used to estimate the average size of individual aggregates and the type, used to identify the form or shape of individual aggregates.
6. **Other morphological data:** root distribution, concretions, krotovinas, coatings, boundary, characteristics biotic activity, etc., were described in terms of size, quantity and abundance.
7. **Horizon designation:** the horizons were designated by master and suffix symbols according to the characteristics of the horizons.

Core samples were also taken from each horizon (see Figure 3.16a and 3.16b) for the determination of bulk density.



a.



b.

Figure 3.16. Taking undisturbed core samples from soil profile

3.2.2 Laboratory Analysis

Soil samples obtained from the profile pits were brought to the laboratory, air-dried ground and sieved through 2 mm mesh size and thereafter used for the determination of physical and chemical properties. Undisturbed soil cores were used for the bulk density determination. The detailed determinations were as follows;

3.2.2.1 Gravel Content

The gravel content of each soil sample was determined from the weight that remained on the sieve after passing through the 2 mm sieve. The percentage gravel content (Gc) was calculated as:

$$G_c = \frac{K}{Q} \quad (1)$$

where K is the mass of gravel and Q is the mass of soil sample.

3.2.2.2 Particle Size Analysis

The Bouyoucos hydrometer method (Bouyoucos, 1962; Day, 1965) was used to determine the primary soil separates (sand, silt and clay). Fifty grams (50 g) of a soil sample (< 2 mm) was added to a beaker and 20 mL of H₂O₂ added to oxidize the organic matter. Then 100 mL of calgon solution (sodium hexametaphosphate and NaHCO₃) was added to the mixture in the beaker and stirred.

The mixture was then heated until it started boiling while stirring and then poured through a 53 µm sieve into a cylinder and made up to the 1000 mL with distilled water. The material which could not pass through the sieve was washed into a beaker and allowed to settle for 24 hours.

After sedimentation, the water was poured off and the sediment was heated to evaporate all moisture in order to obtain the sand fraction.

The particles which passed through the 53 μm sieve were agitated with a plunger and the cylinder left to stand and the time noted. A hydrometer (ASTM 15 2H) was used to read the suspension at 5 minutes and then at 5 hours.

The oven dried samples were transferred to a desiccator and then weighed after cooling to represent the sand fraction. Equations 2 to 5 are the formulae used in determining the percentage weight of sand, silt and clay of each soil sample. The textural triangle (Figure 3.17) was used to determine the textural classes of the soil samples.

$$\text{Silt \%} + \text{Clay \%} = \frac{\text{5 minutes hydrometer reading}}{\text{Weight of soil sample}} \times 100 \quad (2)$$

$$\text{Clay \%} = \frac{\text{5 hours hydrometer reading}}{\text{Weight of soil sample}} \times 100 \quad (3)$$

$$\text{Silt \%} = \% (\text{Silt} + \text{Clay}) - \% (\text{Clay}) \quad (4)$$

$$\text{Sand \%} = \frac{\text{Oven Dry Mass (g) of Particle Retained on the } 53\mu\text{m Sieve}}{\text{Weight of soil sample}} \times 100 \quad (5)$$

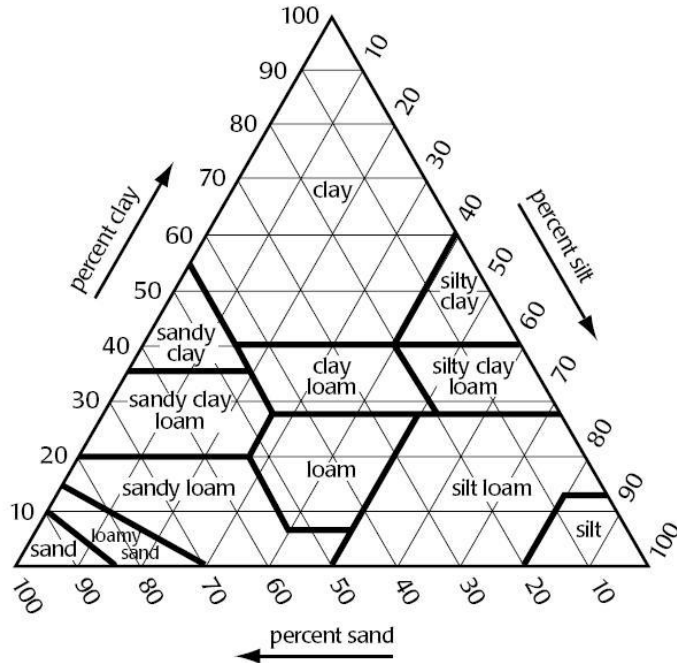


Figure 3.17. Textural triangle for texture determination. Taken from Gee and Or (2002).

3.2.2.3 Bulk Density

Core samples taken from each horizon were weighed and oven dried for 24 hours at 105 °C (Black and Hartge, 1986). The oven dried mass of the samples was recorded. The volume of the cylindrical core sampler (which is the product of internal cross-sectional area and height) was determined and used as the volume of the soil. The bulk density (ρ_b) was calculated using Eq 6.

$$\rho_b = \frac{M_s}{V_t} \quad (6)$$

where M_s is the mass of oven dried sample and V_t is the volume of the cylindrical core sampler.

3.2.2.5 Soil pH (1:1)

Twenty five grams of air dried soil sample (< 2 mm) was weighed into a 50 mL beaker and 25 mL of distilled water added in a ratio of 1:1 (soil: water). The soil suspension was then mixed well by stirring with a glass rod for about 10 minutes. The suspension was then allowed to stand for an hour to allow the suspended particles to settle. The glass electrode of the pH meter was standardized with two aqueous solutions of pH 4 and 7. The pH of the samples was measured by dipping the glass electrode into the supernatant.

3.2.2.6 Soil Electrical Conductivity (1:5)

The concentration of soluble inorganic salts, electrical conductivity (EC), in the soil was determined following the method described by Slavich and Petterson (1993). Five (5) grams of the soil sample was weighed into a 50 mL beaker and 25 mL of distilled water added (a ratio of 1:5, soil: water). The soil suspension was then stirred for 1 hour at 10 minutes interval. The electrical conductivity meter was calibrated with KCl at concentration of 0.01 N and the electrodes dipped into the suspension and reading taken.

3.2.2.7 Total Nitrogen

The total nitrogen content of the soil was determined by a 3-stage method; (1) digestion, (2) distillation and (3) titration (Bremner, 1965). Air-dried soil sample (0.2 g) was weighed into a 250 mL Kjeldahl flask followed by addition of digestion accelerator, selenium catalyst, and 5 mL of concentrated sulphuric acid (H₂SO₄). The mixture was allowed to digest until it was clear. It was allowed to cool and then transferred with distilled water into a 50 mL volumetric flask and made up to the volume. A 5 mL aliquot was pipetted from the digest into a distillation flask and 20 mL of 10 N sodium hydroxide (NaOH) was added with 150 mL distilled water. The sample was then distilled and collected in 25 mL of boric acid. The distillate was titrated

against 0.02 N HCl (Bremner and Mulvaney, 1982) to attain the end point. The amount of N (%) was calculated from Eq. 7.

$$\% N = \frac{14.007 * 0.02 * (A - B)}{0.2 \text{ g} * 1000} \times 100 \quad (7)$$

where 14.007 is the molecular number of Nitrogen, 0.02 is the normality of HCl, A is the sample titre value, B is the titre value of the blank.

3.2.2.8 Organic Carbon

The wet combustion method of Walkley and Black (1934) was used to determine the organic carbon content of the soils. One (1) gram of soil sample was weighed and 10 mL of 1 N potassium dichromate ($K_2Cr_2O_7$) solution was added. Twenty (20) mL of 98% sulphuric acid (H_2SO_4) was added to the prepared mixture and allowed to stand for 2 hours to ensure complete digestion. A 30 mL blank solution was then prepared in a ratio of 1:2 (i.e. 1 mL $K_2Cr_2O_7$ solution and 2 mL H_2SO_4) and the blank factor determined by using Eq. 8.

$$\text{Blank factor (bf)} = \frac{10}{\text{Titre value of the blank solution}} \quad (8)$$

Hundred (100) mL distilled water and 5 mL of concentrated orthophosphoric acid (H_3PO_4) were then added to the mixture. The remaining unreacted $K_2Cr_2O_7$ in the solution after the digestion was titrated against 0.2 M Fe_2SO_4 using 5 drops of diphenylamine [$(C_6H_5)_2NH$] as the indicator to give the end point. The titre value was used to calculate the % C using Eq. 8 – 10.

$$\% \text{ Organic carbon (OC)} = (0.3 [10 - (XN)] 1.33) / W \quad (9)$$

where X = titre value of ferrous ammonium sulphate, N = molarity of ferrous ammonium sulphate and W = weight of soil.

$$\% \text{ Organic Matter (OM)} = 1.724 * \% \text{ Organic carbon} \quad (10)$$

where 1.724 is a constant factor, assuming that OM contains 58% OC.

3.2.2.9 Available Phosphorus

Available P content of the soils was determined using Bray I solution (Bray and Kurtz, 1945). Five (5) grams of soil sample was weighed into an extraction bottle and 35 mL of Bray I solution added. It was then capped and shaken for 30 minutes on a mechanical shaker. The mixture was filtered using Whatman's No. 125 filter paper to obtain a clear filtrate. Five (5) mL aliquot was taken into a test tube and then 10 mL of colour reagent added. A 0.02 g of ascorbic acid was then added to reduce the P to form blue colour. The mixture in the test tube was swirled for colour development and phosphorus analysis. The concentration of P in the mixture was then determined using the spectrophotometer. Available phosphorus content of the soil was calculated by using Eq. 11.

$$\text{Avail. P} = \frac{X}{0.0878} * 7 \quad (11)$$

where X is the absorbance and 7 is the extraction ratio (i.e. 1:7, 5 g soil: 35 mls of Bray I solution).

3.2.2.10 Cation Exchange Capacity

Ammonium acetate (NH₄OAc) pH 7.0 method (Chapman, 1965) was used to determine the CEC of the soil samples. To mimic field conditions, leaching tubes were used. Leaching tubes were stuffed about half-way with cotton wool and 2.5 g of soil sample weighed into them. Fifty (50) mL of NH₄OAc at pH 7 was measured and poured into the leaching tube with the soil sample. The setup was allowed to stand for 2 hours to ensure maximum leaching of exchangeable bases. The leachate was then taken and subjected to analysis. Atomic absorption

spectrophotometer (AAS) was used to determine the concentrations of Magnesium (Mg) and Calcium (Ca) and the flame photometer was used to analyze the leachate for the concentrations of Sodium (Na) and Potassium (K).

3.2.2.11 Exchangeable Acidity and Hydrogen

Exchangeable acidity was determined following the method of McLean et al. (1965). Three grams of soil sample was weighed onto a folded filter paper and placed on an extraction cup. Then 50 mL of 1.0 N KCl solution was gently poured onto the soil on the filter paper. Five (5) drops of phenolphthalein indicator was then added to the soil filtrate and titrated with 0.05 N NaOH to obtain a pink end point. The titre volume (in mL) of NaOH used was then recorded. Equation. 12 was used to calculate the exchangeable acidity of the soil samples.

$$\text{Exchangeable acidity} = \frac{V * 0.05 * 100}{W} \quad (12)$$

where V is the titre volume in mL of NaOH used, 0.05 is the normality of NaOH, W is the weight of soil sample in grams.

Exchangeable aluminium was determined by the addition of four (4) mL of 3 N NaF to the titrated extract and the mixture titrated again with 0.05 N HCl to obtain a pink end point. The titre value of HCl used was then recorded and the amount of exchangeable aluminium in the soil calculated from Eq. 13.

$$\text{Exchangeable aluminium} = \frac{V * 0.05 * 100}{W} \quad (13)$$

where V is the titre volume in mL of HCl used, 0.05 is the normality of HCl, W is the weight of soil sample in grams.

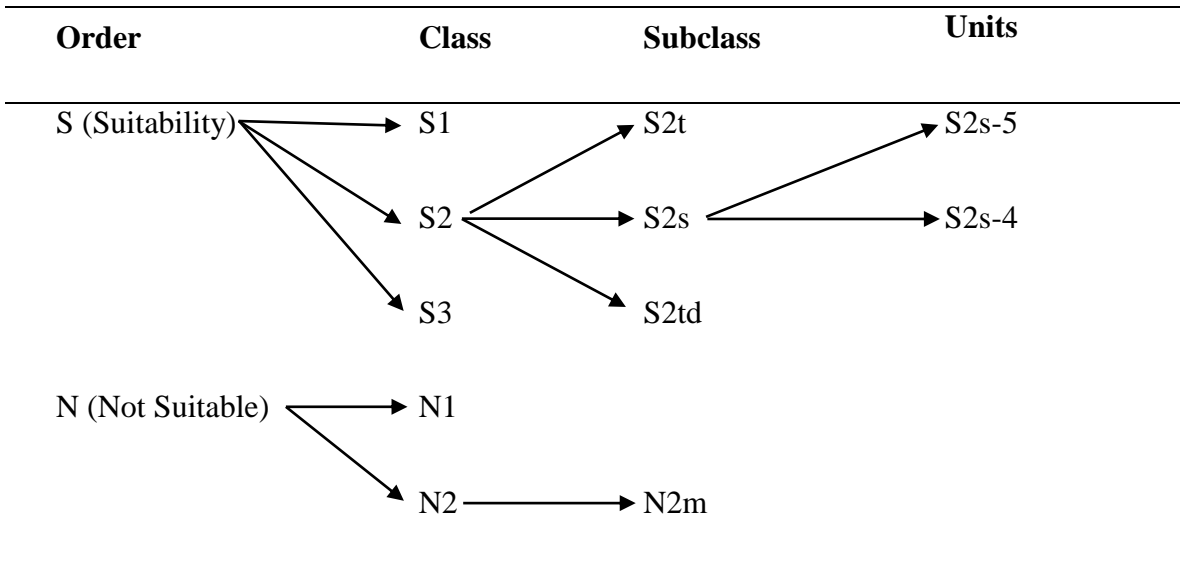
3.2.3 The Soil Quality Index Methodology (SQI)

Parameters used in this study to determine the SQI fell into three categorical datasets; (1) physical and morphological (e.g. soil texture, colour, depth, texture, consistency, structure, root distribution, erosion, gravimetric moisture content, bulk density, porosity, etc.), (2) chemical (e.g. pH, organic carbon, effective cation exchange capacity, exchangeable acidity, available phosphorus, total nitrogen, electrical conductivity, etc.) and (3) climatic (temperature and rainfall).

Using the soil and other data collected (as described above), the FAO (1976) framework was adopted. The rating scheme is shown below in Table 3.3. Soil suitability class specifications were developed ranging from S1 to N2 (S1 – highly suitable, S2 – moderately suitable, S3 – marginally suitable, N1 – marginally not suitable and N2 – permanently not suitable).

Furthermore, FAO (1976) developed the four categorical or hierarchical stages of soil classifications; (1) orders, (2) classes, (3) subclasses and (4) units (Table 3.3). These ratings provide a means for conducting suitability classification, indicating the degrees of suitability within the orders, showing the kinds of limitations associated with the classification or the main kinds of improvement measures required within the class and also reflect the minor differences in the required management within the subclasses (FAO, 1976).

Table 3.3. Structure of the Suitability Classification Scheme. Adapted from FAO (1976).



t = topography, s = structure, d = drainage, m = cementation

For the SQI rating, the properties of interest were:

- I. **Cation exchange capacity (CEC):** according to Rhoades (1982) and Sumner & Miller, (1996), CEC gives a quantitative evaluation of the capacity of soils to hold cations in soil solution. In effect, CEC has a significant effect on the fertility management of the soil, nutrient retention capacity, and the capacity to protect groundwater from cation contamination.

- II. **Soil moisture content:** from the studies of Hillel and Rosenzweig (2002), Ciais et al. (2005) and Farooq et al. (2009) soil moisture is the main limiting SQI in any agricultural ecosystem. As such, it is a critical index for soil functionalities (Mueller et al., 2010). Available moisture content is vital in supporting crop growth and soil biological processes, water budgets estimation, drought prediction, designing of irrigation and drainage systems among others.

- III. Residue management:** crop residues, the primary source of organic matter, play significant roles in stabilizing the agricultural ecosystem by improving soil structure and soil moisture content and retention (Prasad and Power, 1991).
- IV. Soil pH:** it is an indicator of the acidity or alkalinity of soil which controls the mobility and hence the availability of soil nutrients (McLean, 1982; Thomas, 1996).
- V. Total organic carbon (C_{tot}) and total organic nitrogen (N_{tot}):** these components have strong effects on soil fertility status because high amounts of C_{tot} and N_{tot} improve carbon cycle and nitrogen cycle respectively and thereby increases CEC and water holding capacity of the soils (Rasmussen et al., 1980; Nelson et al., 1996).
- VI. C:N ratio:** increasing C:N ratio indicates low heterotrophic activity in soils and thus a vital indicator in estimating soil fertility index (Van et al., 1990).
- VII. Temperature and rainfall:** these parameters are major contributors to the soil formation and microbial activities (Dalal and Mayer, 1986; Russell, 2002) and also, influence many chemical actions in the soil and its environment.
- VIII. Bulk density:** according to Black and Hartge (1986), structural support, water and solute movements, and soil aeration are characteristics of a healthy soil. Measuring bulk densities has been recommended to be important and a significant SQI which expresses soil physico-chemical and biological properties suitable for the assessment of soil quality and comparison of management systems.
- IX. Effective soil depth:** growing plants do well when root growth and movement are not restricted. Thus, root space and effective volume of soil where plants could obtain water

and nutrients are important. Effective soil depth is therefore a key SQI necessary in any soil quality assessment (Rhoton and Lindbo, 1997).

- X. Soil texture:** one of the objectives of this study is to assess SQI with MCA tools. It is therefore important to classify the soils studied based on their textural classes so as to determine crop suitability, infiltration, drainage and possibly estimate the responds of soil texture to environmental and management conditions (Dexter, 2004).
- XI. Slope of topography:** this SQI will help in the assessment of crop slope requirements, drainage, erosional hazards and so on in developing management recommendations (Moore et al., 1993; Fraisse et al., 2001)
- XII. Presence or Depth to hardpan (ironpan):** impedance to root growth, source of water or nutrient is detrimental to plant growth. Presence of or depth to ironpan will be observed and scored for its percentage influence in developing soil quality ratings.

3.2.4 Scoring Soil and Other Properties

For each of these properties whose values were determined in the laboratory or from secondary data, a -1 to 2 score was obtained, depending on the property preference limits as proposed by Mukherejee and Lal (2014).

In order to minimize the subjectivity in assigning rating values to soil the measured properties, equations were derived based on the limits and applied. The functions for the soils properties are as follows (Eq. 14 – 17).

$$\text{pH_score} = 0.0086 * \text{pH}^4 - 0.22 * \text{pH}^3 + 1.79 * \text{pH}^2 - 4.89 * \text{pH} + 2.76 \quad (14)$$

$$\text{SOC_score} = - 0.33 * \text{SOC}^2 + 0.56 * \text{SOC} - 0.097 \quad (15)$$

$$TN_score = - 6.24 * TN^2 + 8.48 * TN - 0.83 \quad (16)$$

$$Avail_P_score = - 0.0023 * Avail_P^2 + 0.10 * Avail_P - 0.0013 \quad (17)$$

The bulk density is considered to affect maize growth due to a mechanical impedance to root growth. This impedance effect derived from a Critical Bulk Density (CBD), above which plant growth begins to be impaired and a Growth Limiting Bulk Density, GLBD, below which growth stops. Pierce et al. (1983) provided the following two functions for the CBD (Eq. 18a) and the GLBD (Eq. 18b).

$$CBD = 0.0175 * \% \text{ Sand} + 0.0168 * \% \text{ Silt} + 0.0122 * \% \text{ Clay} \quad (18a)$$

$$GLBD = 0.0192 * \% \text{ Sand} + 0.0182 * \% \text{ Silt} + 0.0124 * \% \text{ Clay} \quad (18b)$$

and these were used to construct the BD hospitability curve enabling the determination of the bulk density score (BD_score) (Eq 19).

$$BD_score = \min(8.51 * BD^2 - 33.2 * BD + 32.36) \quad (19)$$

where 'min' selects the lowest of the terms in the parenthesis.

The Water Holding Capacity (WHC) was estimated using pedo-transfer function of Ritchie et al. (1999) using texture, bulk density, organic carbon and coarse fractions. The WHC score (WHC_score) was then calculated using Eq. 20.

$$WHC_score = -0.0001 * WHC^2 + 0.29 * WHC \quad (20)$$

The score ranges were not the same for all properties. The BD and available phosphorus (Avail_P) had a range of zero to unity (1) while the others had zero to 2. For the pH, the lowest score was ranked from -1 to 2.

The logical steps used to transform the physico-chemical properties into SQI was based on the procedure of Andrews et al., (2004) (Figure 3.18).

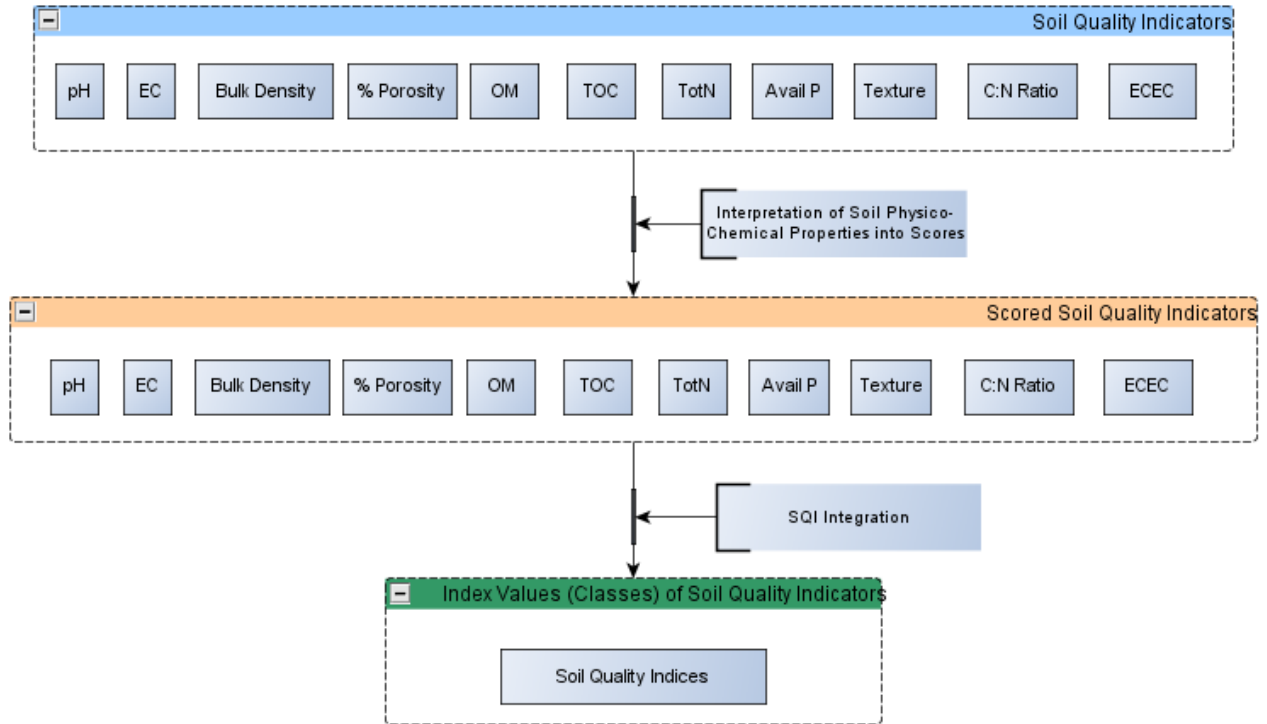


Figure 3.18. Logical steps used to develop SQI.

3.2.5 Statistical Analysis of Soil Quality Indexes

Microsoft Excel (version 2013) was used to enter data. Statistical analyses were also done through Excel. Descriptive statistics (mean, median, standard deviation, range and sample variance) were used to describe the data. Due to the use of multi-criteria tools (MCT) and the possibility of spatial variability of soil quality indexes (SQI), one-way analysis of variance was performed to determine whether the indexes differed statistically between different agro-ecological zones.

An estimate (Coefficient of Variability) of spatial variability of soil properties was determined from a range of values for each horizon of the soils (Brown, 1998; Abdi, 2010). The statistics were expressed at $p \leq 0.05$ level of significance. Pearson's correlation (Wösten and Van, 1988; Adler and Parmryd, 2010; Ayuke et al., 2011; Odgers et al., 2011) was used to examine the degree of association (positive or negative) between the SQIs within the soil profiles. In addition, pairwise comparison of means was conducted to determine the similarity or otherwise of the population means.

3.3 DSSAT Modelling of Test Crop Yield

Maize was selected as the test crop for DSSAT modelling because most of the soil survey assessment was done on maize fields. Thus, these data were used to develop a yield recommendation for the selected MCA alternative. In the DSSAT modelling, crop requirements, soil profile data and weather data were combined in the DSSAT application to simulate the yield for various crop management strategies (Hoogenboom et al., 2004).

The DSSAT crop model (Jones et al., 2003) was used to simulate maize growth for each soil series. The measured soil data were used as input into the model to simulate maize yields for 30 years (1980 to 2010) using weather data from the Ghana Meteorological Agency. Maize intensification was assumed to involve some fertilizer application at a recommended rate of NPK (60 – 40 – 40) (SRID, 2011). The potential maize yield for each location was simulated by assuming a nitrogen application rate of 120 kg N ha^{-1} . The simulated yields for each location were subjected to summary statistics and yield stability was expressed in terms of the coefficient of variation (CV).

3.4 The Multi-criteria Analysis (MCA).

The version of the MCA tool used in this study is by Janssen (2001). The various soil series were considered as alternative locations for maize production and these locations were compared under 8 different criteria, namely: revenue (price x yield, with the yield being the DSSAT simulated mean yield) and the price adjusted for inflation price using the consumer price index. Fertilizer cost was obtained from the Ministry of Food and Agriculture. Entries for soil erosion parameters; namely the erosivity, soil erodibility and erosion control practices by farmers at the various soil series formed other inputs of the MCA. The rainfall erosivity was calculated as the Fournier index (FI; Fournier, 1960) from Eq. 21.

$$FI = \frac{p^2}{P} \quad (21)$$

where p is the peak month rainfall (mm) and P is the annual mean rainfall.

The soil erodibility was calculated from Eq. 22 as the Modified Clay Ratio (MCR; Isikwue et al., 2012):

$$MCR = \frac{(\% \text{ Sand} + \% \text{ Silt})}{(\% \text{ Clay} + \% \text{ SOC})} \quad (22)$$

The entry for soil erosion control was derived from the types of conservation practices implemented by farmers. Practices such as residue retention and ridging were scored higher than bare and clean tillage.

Data on the distance to market from observed sites were calculated by the use of ArcMap software.

All the criteria used were summarized as the Effects Table or evaluation (Table 3.4) based on the procedure used by Stratigea and Grammatikogiannis, (2008).

To arrive at an overall score for each soil series, entries (criteria) of each row were normalized by dividing each entry value (criteria value) by the maximum row value. The normalized values for each soil series were then summed and ranked with respect to the other soil series scores. The stages used in developing the decision support framework was adapted and modified from Stratigea and Grammatikogiannis (2008) (Figure 3.19).

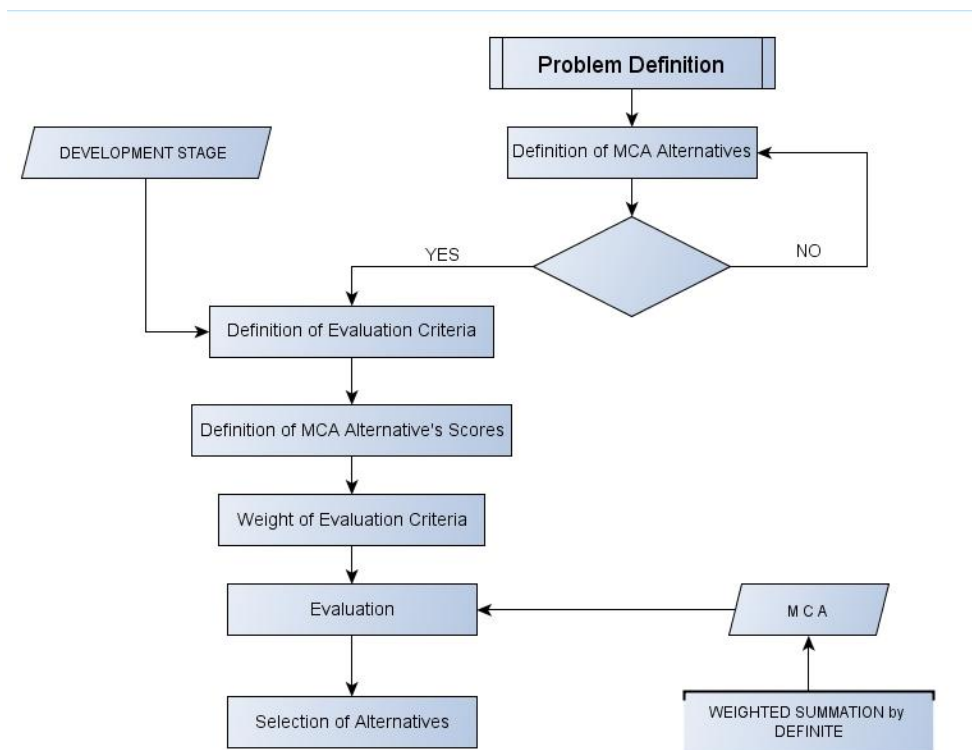


Figure 3.19. Stages used in developing decision support framework.

Table 3.4. The Impact Matrix for assessing MCA Alternatives.

Multi-Criteria Alternatives				
Criteria	1	2	...	I
1	Score _{1,1}	Score _{2,1}	...	Score _{2,1}
2	Score _{2,1}	Score _{2,1}	...	Score _{2,1}
...
J	Score _{2,1}	Score _{2,1}	...	Score _{1,J}

Score_{1,J} is the performance of the alternative I with respect to the criterion J, and Criteira J was an Effect.

3.5 GIS Spatial Mapping of SQIs by Geostatistical Tools

Geostatistical methods of analyzing SQI's have been very effective as they give the freedom to investigate, describe, determine the pattern of variability, visualize and create surfaces from sophisticated statistical methods (Berterretche et al., 2005). Indeed, for studies on the management of agricultural lands, it is very effective to create statistical continuous surfaces to assess the quality of analysis using prediction standard error, probability, quartile and standard error of surfaces. Also, it was possible to determine areas where soil qualities were above or below probability thresholds indicated by optimal interpolation surfaces. This helped to form the fundamental information on which management schemes for agricultural lands could be adapted.

The four main basic steps (data representation, exploration, model fitting and diagnostic analysis) in analyzing soil quality data statistically were used in creating the interpolated management maps (Economic and Social Research Institute, 2001).

CHAPTER FOUR

4.0 RESULTS

4.1 The Chemical and Physical Properties of Soils Studied

4.1.1 Chemical properties of Varempere series

4.1.1.1 Soil pH and electrical conductivity

The pH (H₂O) of Varempere series ranged from 6.5 to 6.7 (Table 4.1). Soil pH decreased with increasing depth. The bottom horizon (52 – 102 cm) recorded the lowest pH of 6.5. However, there was minimal variation in pH of the horizons of the soil.

The surface soil recorded the highest electrical conductivity (EC) of 0.7 dS m⁻¹ (Table 4.1). The subsurface (23 – 38 cm) and the bottom horizon (52 – 102 cm) recorded the lowest EC of 0.2 dS m⁻¹.

4.1.1.2 Organic carbon

The soil contained very small amounts of organic carbon which decreased with depth (Table 4.1). The organic carbon content of the soil ranged from 0.18 to 0.35%. The highest (0.35%) was recorded in the surface soil and the lowest of 0.18% in the bottom horizon.

4.1.1.3 Total nitrogen

The total nitrogen content of the soil was low (Table 4.1). It ranged from 0.02 to 0.08% with the highest amount in the surface soil. The Total N content of the soil decreased with depth.

4.1.1.4 Exchangeable bases

Varempere series showed very low levels of exchangeable bases which tended to increase with depth (Table 4.1). Both the surface and subsurface horizons contained 1.34 cmol_c kg⁻¹ Ca while

the lower horizons contained 2.14 $\text{cmol}_c \text{ kg}^{-1}$ Ca. The amount of exchangeable Mg in the soil ranged from 0.70 $\text{cmol}_c \text{ kg}^{-1}$ in the surface soil to 1.5 $\text{cmol}_c \text{ kg}^{-1}$ in the bottom horizon. The exchangeable K and Na contents of the soil were 0.09 to 0.21 $\text{cmol}_c \text{ kg}^{-1}$ and 0.06 to 0.13 $\text{cmol}_c \text{ kg}^{-1}$ respectively.

The higher concentrations of exchangeable bases in the lower horizons of the soil indicates the effect of leaching.

4.1.1.5 Exchangeable acidity

The exchangeable acidity levels in the soil ranged from 0.10 to 0.13 $\text{cmol}_c \text{ kg}^{-1}$ (Table 4.1).

4.1.1.6 Base saturation

The base saturation of the soil ranged from 94.51 to 97.35% and tended to increase with depth (Table 4.1). The lowest amount (94.5%) was recorded in the surface soil whilst the highest amount (97.35%) was recorded in the third horizon (38 – 52 cm).

4.1.1.7 Available phosphorus

The available phosphorus levels in Vairempere series decreased sharply with depth (Table 4.1). The highest level of 7.41 mg kg^{-1} was recorded in the surface soil and the lowest level of 0.08 mg/kg was in the bottom horizon. The largest change in available P content (i.e. 5.26 mg kg^{-1}) occurred between the surface soil (7.41 mg kg^{-1}) and the subsurface soil (2.15 mg kg^{-1}).

Table 4.1. Chemical properties of Varempere series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-23	6.6	0.7	0.35	0.08	1.34	0.70	0.11	0.09	2.24	0.13	2.37	94.51	7.41
23-38	6.7	0.2	0.24	0.05	1.34	0.80	0.09	0.06	2.29	0.10	2.39	95.82	2.15
38-52	6.6	0.5	0.21	0.05	2.14	1.34	0.12	0.08	3.68	0.10	3.78	97.35	2.31
52-102	6.5	0.2	0.18	0.02	2.14	1.50	0.21	0.13	3.98	0.12	4.10	97.07	0.08

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity,

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

4.1.2 Physical properties of Varempere series

4.1.2.1 Moisture content

The moisture content of Varempere series increased with depth (Table 4.2). It ranged from 0.54 to 1.34%. The lowest moisture content (0.54%) was recorded in the surface soil whilst the highest (1.34%) was recorded in the third horizon (38 – 52 cm) of the soil.

4.1.2.2 Bulk density and porosity

The bulk density of Varempere series ranged from 1.5 to 1.7 Mg m⁻³ and decreased with depth (Table 4.2). The highest bulk density (1.7 Mg m⁻³) was recorded in the surface soil whilst the lowest (1.5 Mg m⁻³) was recorded in the third horizon (38 – 52 cm).

The porosity of Varempere series increased with depth and ranged from 36.2 to 44.2%. The level of porosity of the horizons was inversely related to the bulk density of the horizons.

4.1.2.3 Particle size distribution and texture

The sand content of Varempere series ranged from 80.8% in the surface soil to 64.7% in the bottom horizon (Table 4.2). The silt content of the soil ranged from 12.0 to 19.2%. The bottom horizon contained the highest amount of silt. The clay content of the soil increased with depth from 6.3% in the surface soil to 16.1% in the bottom horizon. The results show that while the sand content of the soil decreased with depth, the silt and clay contents increased with depth. The texture of the soil was loamy sand in the surface and subsurface soils but sandy loam in the subsoil and bottom horizons.

The general site information and profile description of Varempere series are presented in Table 1 and 2 (appendix 2). The profile of Varempere series is shown in Figure 4.1.

Table 4.2. Physical properties of Varempere series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution (< 2 mm, %)			Texture
				Sand	Silt	Clay	
0-23	0.54	1.7	36.15	80.8	12.9	6.3	ls
23-38	1.11	1.6	39.84	79.6	12.0	8.4	ls
38-52	1.34	1.5	44.22	68.1	17.7	14.2	sl
52-102	-	-	-	64.7	19.2	16.1	sl

ls = Loamy sand, sl = Sandy loam

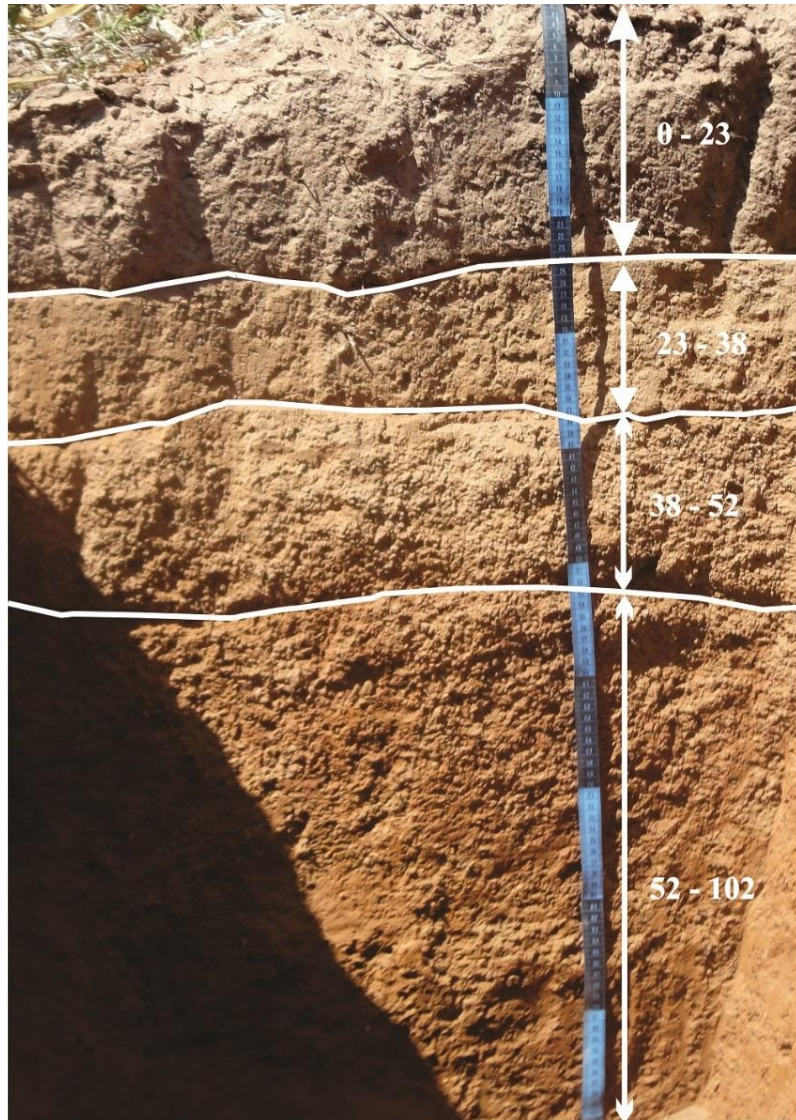


Figure 4.1. Profile of VAREMPERE Series

4.1.3 Chemical properties of Kupela series

4.1.3.1 Soil pH and electrical conductivity

The pH (H₂O) of Kupela series ranged from 6.7 to 7.5 and increased with depth (Table 4.3).

While the surface and subsurface soils showed slightly acidic (near neutral) pH, the lower horizons showed neutral to slightly alkaline pH.

The EC levels of Kupela series were very low (Table 4.3). They ranged from 0.2 to 0.4 dS m⁻¹.

4.1.3.2 Organic carbon

The organic carbon content of Kupela series ranged from 0.77 to 0.38% and decreased with depth (Table 4.3).

4.1.3.3 Total nitrogen

The total nitrogen contents of Kupela series were low and decreased with depth (Table 4.3). The total N levels ranged from 0.14% in the surface soil to 0.04% in the bottom horizon. The distribution of total N in the soil was directly related to the levels of organic carbon in the horizons.

4.1.3.4 Exchangeable bases

The level of exchangeable Ca in Kupela series ranged from 1.34 to 5.34 cmol_c kg⁻¹ (Table 4.3). The bottom horizon contained the highest amount of exchangeable Ca. but the surface and subsurface contained 2.4 cmol_c kg⁻¹ of Ca. The horizons between the subsurface soil and the bottom horizon contained the lowest amounts of exchangeable Ca, 1.34 and 1.87 cmol_c kg⁻¹ respectively. The exchangeable Mg content of Kupela series ranged from 0.09 to 2.80 cmol_c kg⁻¹. Just like Ca, the lowest amounts of exchangeable Mg occurred in the horizons between the subsurface soil and the bottom horizon. Both the surface and subsurface soils contained 1.2 cmol_c kg⁻¹ Mg.

The exchangeable K content of Kupela series ranged from 0.07 to 0.51 cmol_c kg⁻¹. The bottom horizon contained the highest amount of exchangeable K followed by the surface soil (0.22 cmol_c kg⁻¹) and the subsurface soil (0.14 cmol_c kg⁻¹). The third horizon (43 – 80 cm) contained

the smallest amount of exchangeable K. The level of exchangeable Na in Kupela series ranged from 0.05 cmol_c kg⁻¹ in the middle horizon to 0.20 cmol_c kg⁻¹ in the bottom horizon.

The results (Table 4.3) show that the exchangeable bases accumulated in the bottom horizons as an indication of leaching from the surface soil. The surface soil might have received farmyard manure and/or were incorporated with crop residue to have such relatively high levels of exchangeable bases.

4.1.3.5 Exchangeable acidity

The exchangeable acidity levels in the soil ranged from 0.05 to 0.12 cmol_c kg⁻¹ (Table 4.3). In both the surface and subsurface horizons, the highest level of 0.12 cmol_c kg⁻¹ was recorded whilst the lowest level (0.05 cmol_c kg⁻¹) was recorded in the last three horizons.

4.1.3.6 Base saturation

The base saturation of Kupela series ranged from 96.84 to 99.44% (Table 4.3). The bottom horizon (105 – 122 cm) recorded the highest amount (99.44%) whilst the lowest amount (96.84%) was recorded in the surface soil.

4.1.3.7 Available phosphorus

The soil was poor in available phosphorus (0.4 – 1.2 mg kg⁻¹) (Table 4.3). The surface soil and the bottom horizons recorded the same amounts of available P content (i.e. 1.20 mg kg⁻¹).

4.1.4 Physical properties of Kupela series

4.1.4.1 Moisture content

The moisture content of Kupela series ranged from 6.73% in the surface soil to 11.93% in the third horizon (43 – 80 cm).

4.1.4.2 Bulk density and porosity

The bulk density of the soil ranged from 1.5 to 1.9 Mg m⁻³ (Table 4.4). The highest bulk density of 1.9 Mg m⁻³ was recorded in the bottom horizon (105 – 122 cm) whilst the lowest (1.5 Mg m⁻³) occurred in the second horizon (21 – 43 cm) of the soil.

The level of porosity of Kupela series was inversely related to the bulk density of the soil (Table 4.4). The highest porosity (44.2%) was recorded in the subsurface horizon whilst the lowest (28.7%) was recorded in the bottom horizon of the soil.

4.1.4.3 Particle size distribution and texture

The particle size distribution of Kupela series ranged from 62.02 to 69.68% (sand), 23.88 to 32.52% (silt) and 2.40 to 14.1% (clay) (Table 4.4). Sandy loam texture was recorded in all the horizons of the soil. The soil contained relatively smaller amount of clay especially in its third horizon (43 – 80cm). The amount of sand in the soil did not vary much throughout the profile.

The general site information and profile description of Kupela series are presented in Table 3 and 4 (appendix 2). The profile of Kupela series is shown in Figure 4.2.

Table 4.3. Chemical properties of Kupela series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmolc kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-21	6.7	0.3	0.77	0.14	2.40	1.20	0.22	0.15	3.97	0.12	4.09	97.07	1.20
21-43	6.7	0.4	0.69	0.11	2.40	1.20	0.14	0.08	3.82	0.12	3.94	96.95	0.40
43-80	7.0	0.2	0.44	0.08	1.34	0.07	0.07	0.05	1.53	0.05	1.58	96.84	0.72
80-105	7.4	0.3	0.38	0.07	1.87	1.00	0.14	0.08	3.09	0.05	3.14	98.41	0.88
105-122	7.5	0.2	0.38	0.04	5.34	2.80	0.51	0.20	8.85	0.05	8.9	99.44	1.20

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity,

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

Table 4.4. Physical properties of Kupela series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand ——	Silt (< 2 mm, %)	Clay ——	
0-21	6.73	1.60	41.0	67.7	25.90	6.40	sl
21-43	11.60	1.50	44.2	68.24	25.46	6.30	sl
43-80	11.93	1.60	38.5	65.08	32.52	2.40	sl
80-105	11.75	1.80	31.9	69.68	24.32	6.00	sl
105-122	9.09	1.89	28.7	62.02	23.88	14.10	sl

sl = Sandy loam

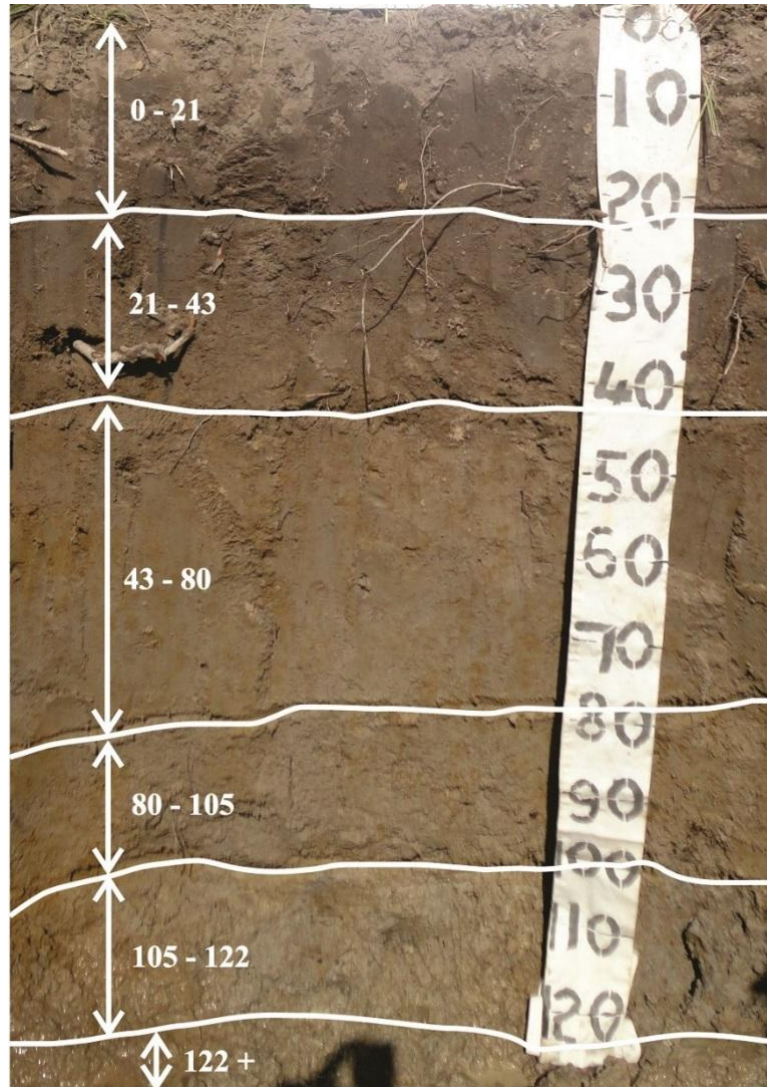


Figure 4.2. Profile of Kupela Series

4.1.5 Chemical properties of Kpelesawgu series

4.1.5.1 Soil pH and electrical conductivity

The pH of Kpelesawgu series ranged from 6.7 to 7.2 (Table 4.5). The highest pH of 7.2 was recorded in both the subsurface and bottom horizons of the soil.

The electrical conductivity (EC) of the soil ranged from 0.3 to 0.4 dS m⁻¹ (Table 4.5). In the surface and subsurface horizons, the same EC of 0.3 dS m⁻¹ was recorded.

4.1.5.2 Organic carbon

The organic carbon content of Kpelesawgu series decreased with depth (Table 4.5). The highest level of 1.48% of O.C was recorded in the surface horizon whilst the lowest (0.31%) was recorded in the bottom horizon (74 – 115 cm).

4.1.5.3 Total nitrogen

The total nitrogen levels in Kpelesawgu series was very low (0.17 – 0.05%) (Table 4.5) which might be partly due to low levels of organic carbon content of the soil. The lowest level (0.05%) was recorded in the bottom horizon (74 – 115 cm) whilst the highest level of 0.17% was recorded in the surface soil.

4.1.5.4 Exchangeable bases

The levels of exchangeable bases of Kpelesawgu series increased with depth (Table 4.5). The surface horizon contained the lowest levels of the exchangeable bases (i.e. Ca = 2.40, Mg = 1.70, K = 0.10 and Na = 0.06 cmol_c kg⁻¹) whilst the bottom horizons recorded the highest levels of 8.81, 6.30, 0.32 and 0.13 cmol_c kg⁻¹ of Ca, Mg, K and Na respectively. The relatively higher concentration of exchangeable bases in the lower horizons of the soil indicates the effect of leaching.

4.1.5.5 Exchangeable acidity

The exchangeable acidity levels in the soil ranged from 0.05 (in both the second and bottom horizons) to 0.12 cmol_c kg⁻¹ in the surface soil (Table 4.5).

4.1.5.6 Base saturation

The base saturation of the soil increased with depth (Table 4.5). The base saturation levels in Kpelesawgu series ranged from 97.26 to 99.68% and increased with depth. The highest amount

of base saturation occurred in the bottom horizon (74 – 115 cm) whilst the lowest level was recorded in the surface horizon.

4.1.5.7 Available phosphorus

The available phosphorus level of Kpelesawgu series ranged from of 1.44 to 1.99 mg kg⁻¹ and decreased with depth (Table 4.5). The highest level (1.99 mg kg⁻¹) was recorded in the surface horizon whilst the lowest (1.44 mg kg⁻¹) occurred in the bottom horizon of the soil.

4.1.6 Physical properties of Kpelesawgu series

4.1.6.1 Moisture content

The soil moisture content of Kpelesawgu series increased with depth (Table 4.6). The bottom horizon recorded the highest moisture content of 7.70% whilst the surface horizon recorded the lowest of 3.42%.

4.1.6.2 Bulk density and porosity

The bulk density of the surface horizon was lowest (1.44 Mg m⁻³) and highest (1.68 Mg m⁻³) in the subsurface horizon of the soil.

The porosity of the soil decreased with depth and was inversely related to the bulk density. The level of porosity ranged from 36.43 to 45.64%.

4.1.6.3 Particle size distribution and texture

The sand content of Kpelesawgu series ranged from 50.28% in the surface soil to 50.68% in the bottom horizon (Table 4.6). The silt content of the soil ranged from 35.32 to 39.72%. The bottom horizon contained the lowest amount of silt. The clay content of the soil increased with depth from 10.0% in the surface soil to 14.0% in both the subsurface and bottom horizons.

Table 4.5. Chemical properties of Kpelesawgu series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-13/24	6.7	0.3	1.48	0.17	2.40	1.70	0.10	0.06	4.26	0.12	4.38	97.26	1.99
13/24-74	7.2	0.3	0.38	0.06	2.94	2.10	0.24	0.08	5.36	0.05	5.41	99.08	1.91
74-115	7.2	0.4	0.31	0.05	8.81	6.30	0.32	0.13	15.56	0.05	15.61	99.68	1.44

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

Table 4.6. Physical properties of Kpelesawgu series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand	Silt (< 2 mm, %)	Clay	
0-13/24	3.42	1.44	45.64	50.28	39.72	10.00	1
13/24-74	7.70	1.68	36.43	50.52	35.48	14.00	1
74-115	-	-	-	50.68	35.32	14.00	1

1 = loamy

The results show that the sand content of the soil remained almost the same throughout the profile. The texture of the soil was loamy throughout the horizons of the soil.

The general site information and profile description of Kpelesawgu series are presented in Table 5 and 6 (appendix 2). The profile of Kpelesawgu series is shown in Figure 4.3.



Figure 4.3. Profile of Kpelesawgu Series

4.1.7 Chemical properties of Lima series

4.1.7.1 Soil pH and electrical conductivity

The pH (H₂O) of Lima series ranged from 6.8 to 7.5 and decreased with increasing depth (Table 4.7). The bottom horizon (95 – 125 cm) recorded the highest pH of 7.5 whilst the lowest pH of 6.8 was recorded in the third horizon (20 – 38 cm).

The electrical conductivity (EC) of Lima series was low and ranged from 0.3 to 0.7 dS m⁻¹ (Table 4.7). The surface soil (0 – 11 cm) recorded the highest EC of 0.69 dS m⁻¹. There was a gradual increase in EC levels with depth.

4.1.7.2 Organic carbon

The soil contained small amounts of organic carbon which decreased with depth (Table 4.7). The levels ranged from 0.09 to 0.69%. The surface soil contained the highest amount of O.C.

4.1.7.3 Total nitrogen

The total nitrogen content of Lima series was low (0.01 - 0.12%) with the highest amount occurring in the surface horizon (Table 4.7). The lowest amount was recorded in the fifth horizon (63 – 95 cm) of the soil.

4.1.7.4 Exchangeable bases

The levels of exchangeable bases in Lima series increased with depth (Table 4.7). The bottom horizon contained the highest amount of Ca (4.81 cmol_c kg⁻¹) while the third horizon contained the lowest amount (1.87 cmol_c kg⁻¹). The amounts of exchangeable Mg in the soil ranged from 1.10 cmol_c kg⁻¹ in the subsurface horizon to 2.50 cmol_c kg⁻¹ in the bottom horizon. The exchangeable K and Na contents of the soil were 0.09 to 0.23 cmol_c kg⁻¹ and 0.08 to 0.13 cmol_c kg⁻¹ respectively.

4.1.7.5 Exchangeable acidity

The exchangeable acidity levels in the soil were very low and ranged from 0.05 to 0.10 $\text{cmol}_c \text{kg}^{-1}$ (Table 4.7).

4.1.7.6 Base saturation

The base saturation of Lima series generally increased with depth (Table 4.7). It ranged from 96.67 to 99.35%. The highest amount was recorded in the bottom horizon while the lowest was recorded in the third horizon (30 – 38 cm) of the soil.

4.1.7.7 Available phosphorus

The available P content of Lima series was low (1.0 to 4.9 mg kg^{-1}) (Table 4.7). The highest amount was recorded in the surface horizon while the lowest level occurred in the fifth horizon (63 – 95 cm). The largest change in available P content (i.e. 1.7 mg kg^{-1}) occurred between the surface horizon (4.86 mg kg^{-1}) and the subsurface horizon (3.11 mg kg^{-1}) of the soil.

4.1.8 Physical properties of Lima series

4.1.8.1 Moisture content

The moisture content of Lima series ranged from 0.66 to 3.20% (Table 4.8). The highest moisture content was recorded in the bottom horizon whilst the lowest level occurred in the surface horizon.

4.1.8.2 Bulk density and porosity

The bulk density of Lima series ranged from 1.59 to 1.84 Mg m^{-3} (Table 4.8). The bottom horizon recorded the highest bulk density whilst the lowest bulk density occurred in the subsurface horizon. Below the surface soil, the bulk density of the soil increased with depth.

The level of porosity of the soils ranged from 30.57% in the bottom horizon to 40.68% in the third horizon (20 – 38 cm) (Table 4.8).

4.1.8.3 Particle size distribution and texture

The amount of sand in the soil decreased with depth (Table 4.8). It ranged from 71.12% in the surface soil to 52.70% in the sand to last horizon (63 – 95 cm). The amount of silt in the soil ranged from 21.62 to 29.10%. The surface soil had the lowest amount of clay (6.20%). The amount of clay increased gradually up to the third horizon and then sharply to the fourth horizon (18.00%). The levels remained almost the same in the fifth horizon and then increased in the bottom horizon to 24.40%. The soil was sandy loam throughout the profile except being sandy clay loam in the bottom horizon.

Table 4.7. Chemical properties of Lima series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — % —	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac. —————	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-11	7.1	0.3	0.69	0.12	3.47	1.80	0.12	0.13	5.52	0.05	5.57	99.10	4.86
11-20	7.0	0.4	0.44	0.09	2.14	1.10	0.09	0.08	3.41	0.10	3.51	97.15	3.11
20-38	6.8	0.3	0.21	0.04	1.87	0.80	0.12	0.11	2.90	0.10	3.00	96.67	1.67
38-63	6.9	0.3	0.30	0.05	2.67	1.30	0.14	0.11	4.22	0.10	4.32	97.69	1.28
63-95	7.2	0.5	0.09	0.01	3.74	1.70	0.23	0.11	5.78	0.05	5.83	99.14	0.96
95-125	7.5	0.7	0.11	0.02	4.81	2.50	0.15	0.13	7.59	0.05	7.64	99.35	1.12

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

Table 4.8. Physical properties of Lima series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand ——	Silt (< 2 mm, %)	Clay ——	
0-11	0.69	1.73	34.6	71.12	22.68	6.20	sl
11-20	0.66	1.59	39.85	68.62	23.28	8.10	sl
20-38	0.75	1.57	40.68	66.18	25.42	8.40	sl
38-63	0.73	1.66	37.18	55.90	26.10	18.00	sl
63-95	1.96	1.77	33.06	52.70	29.10	18.20	sl
95-125	3.20	1.84	30.57	53.98	21.62	24.40	scl

sl = sandy loam, scl = sandy clay loam

The general site information and profile description of Lima series are presented in Table 7 and 8 (appendix 2). The profile of Lima series is shown in Figure 4.4.

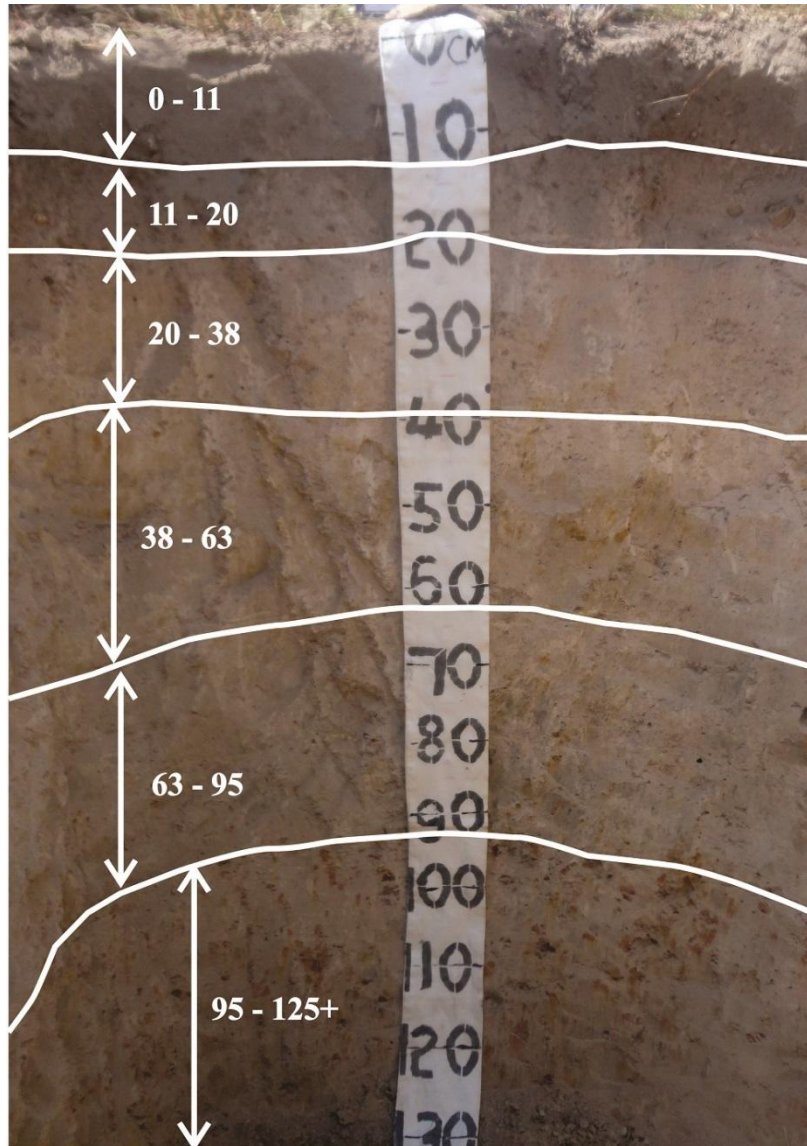


Figure 4.4. Profile of Lima Series

4.1.9 Chemical properties of Ejura series

4.1.9.1 Soil pH and electrical conductivity

The pH (H₂O) of Ejura series ranged from 5.8 to 6.8 (Table 4.9). The surface soil recorded the highest pH (6.8). The lowest pH of 5.8 was recorded in the 51 – 85 cm depth of the soil.

The electrical conductivity (EC) level in the soil was very low (Table 4.9). It ranged from 0.3 dS m⁻¹ in the lower horizons through 0.4 dS m⁻¹ in the subsurface horizons to 0.5 dS m⁻¹ in the surface soil.

4.1.9.2 Organic carbon

The soil contained small amounts of organic carbon (0.07 – 0.35%) which decreased with depth (Table 4.9). The subsurface horizon contained the same amount of organic carbon (0.30%). The highest amount of 0.35% was recorded in the surface soil while the lowest level of 0.07% occurred in the bottom horizon of the soil.

4.1.9.3 Total nitrogen

The total nitrogen content of Ejura series ranged from 0.03 to 0.08% and decreased with depth (Table 4.9). The highest surface soil contained the highest amount of total N (0.08%) while the bottom horizon contained the smallest amount (0.03%).

4.1.9.4 Exchangeable bases

Ejura series showed low levels of exchangeable bases which tended to increase with depth (Table 4.9). The surface horizon contained the lowest Ca amount of (1.87 cmol_c kg⁻¹) while the fourth horizon (113 – 140 cm) contained the highest (4.01 cmol_c kg⁻¹) level of Ca. The amount of exchangeable Mg in the soil ranged from 0.90 cmol_c kg⁻¹ in the surface soil to 2.10 cmol_c kg⁻¹ in the bottom horizon. The exchangeable K and Na contents of the soil were 0.11 to

0.15 $\text{cmol}_c \text{ kg}^{-1}$ and 0.08 to 0.18 $\text{cmol}_c \text{ kg}^{-1}$ respectively. They also tended to increase with depth.

4.1.9.5 Exchangeable acidity

The exchangeable acidity levels in the soil ranged from 0.11 in the surface soil to 0.35 $\text{cmol}_c \text{ kg}^{-1}$ in the third horizon of the soil (Table 4.9).

4.1.9.6 Base saturation

The base saturation of the soil was high (93.06 to 96.81%) (Table 4.9). The bottom horizon had the highest base saturation while the middle horizon (51 – 85 cm) had the lowest.

4.1.9.7 Available phosphorus

The available P level in Ejura series decreased sharply with depth from the surface soil (4.62 mg kg^{-1}) to 1.99 mg/kg in the subsurface horizon (Table 4.9). It decreased further to 1.36 mg kg^{-1} in the middle horizon and then sharply to 0.24 mg kg^{-1} in the fourth horizon. In the bottom horizon, it increased to 0.80 mg kg^{-1} .

4.1.10 Physical properties of Ejura series

4.1.10.1 Moisture content

The moisture content of Ejura series increased with depth (Table 4.10). It ranged from 5.22% in the subsurface horizon (32 – 51 cm) to 12.41% in the bottom horizon (113 – 140 cm).

4.1.10.2 Bulk density and porosity

The bulk density of Ejura series ranged from 1.63 to 1.80 Mg m^{-3} (Table 4.10). The highest bulk density was recorded in the bottom horizon while the lowest occurred in the surface soil.

The porosity of the soil ranged from 32.2 to 38.6%. The level of porosity was inversely related to the bulk density.

4.1.10.3 Particle size distribution and texture

The sand content of Ejura series was high (57.32 – 72.18%) and tended to decrease with depth (Table 4.10).

The silt content ranged from 14.62% in the subsurface horizon to 23.82% in the surface horizon.

The clay content of the soil which tended to increase with depth ranged from 4.00 to 22.00%.

The results showed that while the sand and silt contents of the soil tended to decrease with depth, the clay level showed the reverse trend. A sharp increase was recorded in clay content from the surface horizon to the subsurface horizon of the soil. All the horizons of Ejura series were sandy loam except the fourth horizon (51 – 113 cm) which was sandy clay loam.

Table 4.9. Chemical properties of Ejura series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — % —	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-32	6.8	0.5	0.35	0.08	1.87	0.90	0.11	0.08	2.96	0.11	3.07	96.42	4.62
32-51	6.3	0.4	0.30	0.06	2.67	1.40	0.13	0.08	4.28	0.15	4.43	96.61	1.99
51-85	5.8	0.4	0.30	0.06	2.94	1.50	0.14	0.11	4.69	0.35	5.04	93.06	1.36
85-113	5.9	0.3	0.13	0.03	4.01	2.00	0.12	0.13	6.26	0.30	6.56	95.43	0.24
113-140	6.1	0.3	0.07	0.03	3.74	2.10	0.15	0.18	6.07	0.20	6.27	96.81	0.80

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

Table 4.10. Physical properties of Ejura series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand ——	Silt (< 2 mm, %)	Clay ——	
0-32	5.39	1.63	38.59	72.18	23.82	4.00	sl
32-51	5.22	1.72	35.11	71.08	14.62	14.30	sl
51-85	6.38	1.66	37.39	62.20	21.60	16.20	sl
85-113	10.71	1.75	33.78	57.32	20.68	22.00	scl
113-140	12.41	1.80	32.22	59.76	20.04	20.20	sl

sl = Sandy loam, scl = Sandy clay loam

The general site information and profile description of Ejura series are presented in Table 9 and 10 (appendix 2). The profile of Ejura series is shown in Figure 4.5.

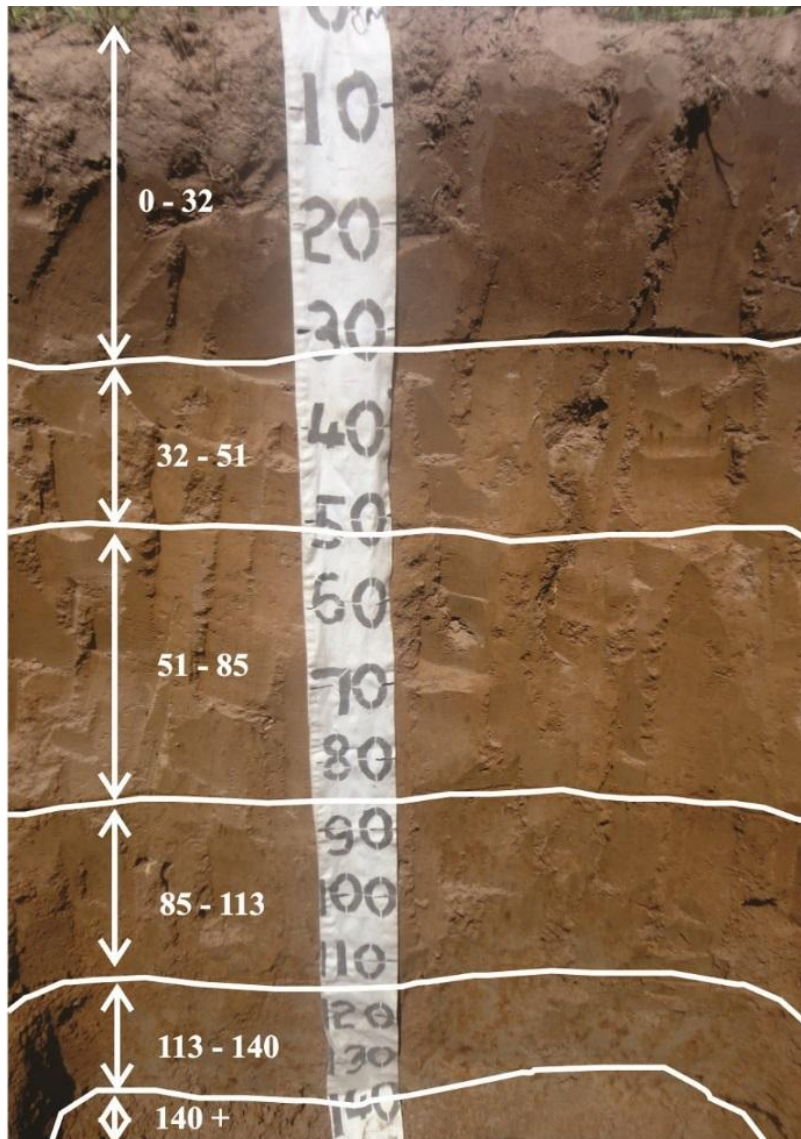


Figure 4.5. Profile of Ejura Series

4.1.11 Chemical properties of Damongo series

4.1.11.1 Soil pH and electrical conductivity

The pH (H₂O) of Damongo series ranged from 5.8 to 6.7 (Table 4.11). The highest pH of 6.7 was recorded in the surface horizon while the lowest (5.8) occurred both in the third (36 – 71 cm) and fourth (71 – 101 cm) horizons.

The electrical conductivity (EC) of the soil decreased with depth (Table 4.11). It ranged from 0.1 to 0.4 dS m⁻¹. In the subsurface and third horizons of the soil, the same EC (0.2 dS m⁻¹) was recorded. Also, the EC level of 0.1 dS m⁻¹ was recorded in the fourth through to the bottom horizons of the soil.

4.1.11.2 Organic carbon

The organic carbon content of Damongo series ranged from 0.13 to 0.45% and decreased with depth (Table 4.11). The same level of organic carbon (0.29%) was recorded in the subsurface and the horizons. The highest organic carbon content was recorded in the surface horizon while the lowest level occurred in the bottom horizon of the soil.

4.1.11.3 Total nitrogen

The total nitrogen content of Damongo series was very low (0.02 to 0.08%) and decreased with depth (Table 4.11). The highest amount (0.08%) was recorded in the surface horizon of the soil while the lowest level (0.02%) occurred in the fifth and bottom horizons of the soil.

4.1.11.4 Exchangeable bases

The levels of exchangeable bases in Damongo series below the surface soil tended to increase with depth (Table 4.11). The surface soil and a lower horizon (101 – 135 cm) contained the highest amount of exchangeable Ca (2.94 cmol_c kg⁻¹). The highest amount of exchangeable Mg

(1.90 $\text{cmol}_c \text{ kg}^{-1}$) occurred in the fourth horizon (101 – 135 cm) of the soil while the lowest level (0.90 $\text{cmol}_c \text{ kg}^{-1}$) was recorded in the subsurface horizons. The amount of exchangeable K and Na were very low. They ranged from 0.12 – 0.20 $\text{cmol}_c \text{ kg}^{-1}$ and 0.08 – 0.13 $\text{cmol}_c \text{ kg}^{-1}$ respectively. Generally, the fifth horizon (101 – 135 cm) recorded the highest levels of the exchangeable bases.

4.1.11.5 Exchangeable acidity

The exchangeable acidity levels in Damongo series ranged from 0.10 $\text{cmol}_c \text{ kg}^{-1}$ (in both the surface and subsurface horizons) to 0.35 $\text{cmol}_c \text{ kg}^{-1}$ in the fourth horizon of the soil (Table 4.11).

4.1.11.6 Base saturation

The base saturation of Damongo series ranged from 89.61 to 97.97% (Table 4.11). The surface horizon of the soil recorded the highest base saturation (97.97%) while the lowest level was recorded in the lower horizon (71 – 101 cm) of the soil.

4.1.11.7 Available phosphorus

The available P content of the surface soil was the highest (4.94 mg kg^{-1}) whilst the lowest level occurred in the fifth horizon (101 – 135 cm) of the soil (Table 4.11). The level of available phosphorus recorded ranged from 0.16 to 4.94 mg kg^{-1} . Between the surface and the subsurface (22 – 36 cm) horizons, the largest change of available phosphorus content was recorded. The largest change in the level of available P (2.63 mg kg^{-1}) occurred between the surface soil (4.94 mg kg^{-1}) and the surface soil (2.31 mg kg^{-1}).

Table 4.11. Chemical properties of Damongo series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-22	6.7	0.4	0.45	0.08	2.94	1.60	0.20	0.08	4.82	0.10	4.92	97.97	4.94
22-36	6.4	0.2	0.29	0.06	1.34	0.90	0.12	0.11	2.47	0.10	2.57	96.11	2.31
36-71	5.8	0.2	0.29	0.05	1.87	0.90	0.16	0.08	3.01	0.30	3.31	90.94	1.83
71-101	5.8	0.1	0.25	0.05	1.87	0.90	0.14	0.11	3.02	0.35	3.37	89.61	0.80
101-135	5.9	0.1	0.19	0.02	2.94	1.90	0.19	0.13	5.16	0.30	5.46	94.51	0.16
135-159	6.1	0.1	0.13	0.02	2.67	1.70	0.14	0.11	4.62	0.20	4.82	95.85	0.24

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity, ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

4.1.12 Physical properties of Damongo series

4.1.12.1 Moisture content

The moisture content of Damongo series increased with depth and ranged from 1.55 to 13.13% (Table 4.12). The lowest moisture content (1.55%) was recorded in the subsurface horizon while the highest of 13.13% was recorded in the fifth horizon of the soil.

4.1.12.2 Bulk density and porosity

The bulk density ranged from 1.3 to 1.7 Mg m⁻³ (Table 4.12). The surface soil had the lowest bulk density (1.3 Mg m⁻³). Below the surface soil, the level of bulk density increased and remained almost uniform between 1.6 to 1.7 Mg m⁻³ till the bottom horizon.

The level of porosity of the soil was inversely related to the bulk density of the soil. It ranged from 37.1 to 50.6% and decreased with increasing bulk density. The surface soil recorded the highest level (50.6%) while the lowest level (37.1%) occurred in the bottom horizon of the soil.

4.1.12.3 Particle size distribution and texture

The sand content of Damongo series ranged from 27.28 to 65.20% (Table 4.12). Below the surface soil, the level of sand tended to decrease with depth. The silt content of the soil ranged from 26.72% to 68.52%. The surface soil had the highest amount of silt, more than twice the level in the horizons below it. The clay content of the soil tended to increase with depth. The smallest amount of clay occurred in the surface soil (4.20%). The level of clay increased to 6.00% in the subsurface soil and then to 12.40% in the next lower horizon. There was a sharp increase in the clay content (< 20.00%) of the lower horizons. The surface soil was silty loam whereas the subsurface horizons were sandy loam. The texture of the fourth horizon was sandy clay loam and underlain with loamy horizons.

Table 4.12. Physical properties of Damongo series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand ——	Silt (< 2 mm, %)	Clay ——	
0-22	2.99	1.3	50.58	27.28	68.52	4.20	sil
22-36	1.55	1.6	40.05	65.20	28.80	6.00	sl
36-71	5.56	1.7	37.66	53.64	33.96	12.40	sl
71-101	10.08	1.7	37.69	51.18	26.72	22.10	scl
101-135	13.13	1.6	39.36	43.06	32.74	24.20	l
135-159	12.41	1.7	37.05	45.78	33.82	20.40	l

sil = Silty loam, sl = Sandy loam, l = Loam

The general site information and profile description of Damongo series are presented in Table 11 and 12 (appendix 2). The profile of Damongo series is shown in Figure 4.6.

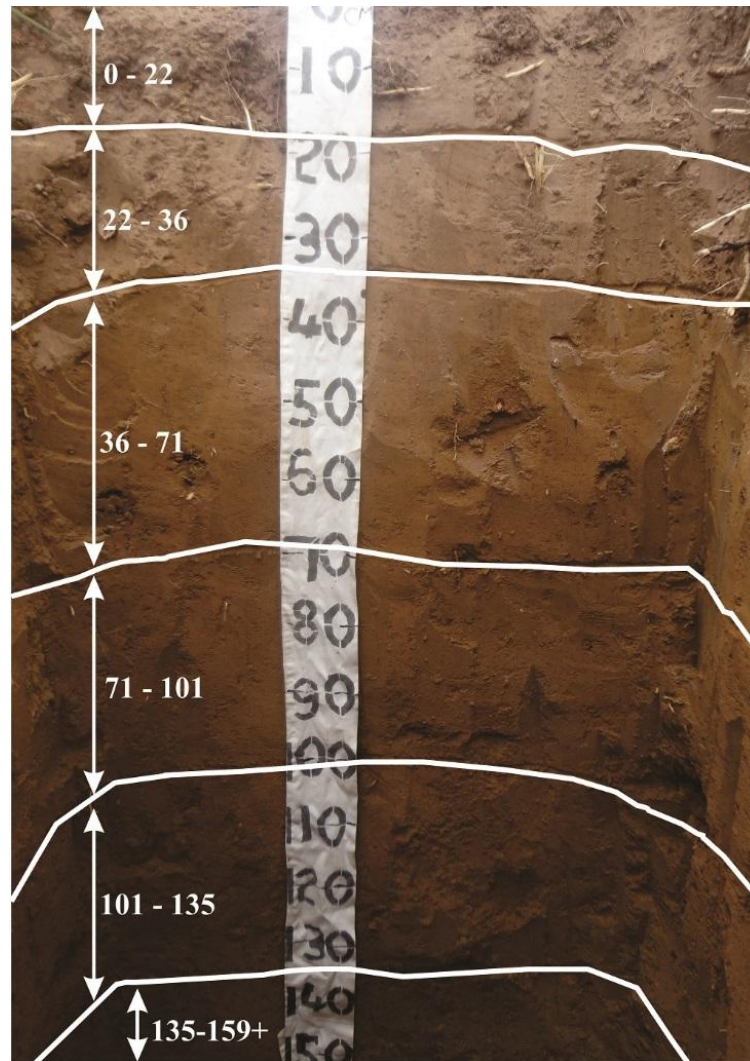


Figure 4.6. Profile of Damongo Series

4.1.13 Chemical properties of Mimi series

4.1.13.1 Soil pH and electrical conductivity

The pH (H₂O) of Mimi series ranged from 5.7 to 6.1 (Table 4.13). The highest pH level of 6.1 was recorded in the subsurface horizon (40 – 58 cm) while the lowest occurred in the surface horizon (0 – 22 cm) of the soil.

The EC was 0.2 dS m⁻¹ throughout the soil profile (Table 4.13).

4.1.13.2 Organic carbon

Organic carbon content of the soil ranged from 0.04 to 0.37% and decreased sharply with depth (Table 4.13). The highest amount of 0.37% was recorded in the surface soil while the lowest (0.04%) occurred in the bottom horizon of the soil.

4.1.13.3 Total nitrogen

The total nitrogen contents of Mimi series was low (0.01 to 0.08%) and decreased with depth (Table 4.13). The distribution of total N in the soil was inversely related to that of organic C content of the soil.

4.1.13.4 Exchangeable bases

The levels of exchangeable bases in Mimi series were low and ranged from 1.34 to 2.94 cmol_c kg⁻¹ (Ca), 1.50 to 2.20 cmol_c kg⁻¹ (Mg), 0.14 to 0.27 cmol_c kg⁻¹ (K) and 0.06 to 0.11 cmol_c kg⁻¹ (Na). Whereas the fourth horizon (58 – 114 cm) contained the highest amount of Ca and Mg, the third horizon (40 – 58 cm) had the highest amounts of K and Na. the surface and subsurface horizons of Mimi series showed high amounts of Mg than Ca.

4.1.13.5 Exchangeable acidity

The exchangeable acidity levels in Mimi series ranged from 0.10 cmol_c kg⁻¹ (in both the surface and subsurface horizons) to 0.35 cmol_c kg⁻¹ in the fourth horizon of the soil (Table 4.13).

4.1.13.6 Base saturation

The base saturation of the soil generally increased with depth (Table 4.13). It ranged from 92.08% in the surface horizon to 97.63% in the fourth horizon (58 – 114 cm) of the soil.

4.1.13.7 Available phosphorus

The level of available phosphorus in the soil decreased with depth (Table 4.13). The highest level (7.65 mg kg⁻¹) was recorded in the surface soil while the lowest (0.24 mg kg⁻¹) occurred in the bottom horizon. The largest change in available P (6.61 mg kg⁻¹) occurred between the surface (0 – 22 cm) and subsurface (22 – 40 cm) horizons. On the other hand, the lowest change (0.08 mg kg⁻¹) occurred between the fourth and bottom horizons of the soil.

4.1.14 Physical properties of Mimi series

4.1.14.1 Moisture content

The moisture content of Mimi series increased with depth (Table 4.14). It ranged from 0.40 to 12.96%. The lowest (0.40%) was recorded in the surface horizon whilst the highest (12.96%) occurred in the bottom horizon of the soil.

Table 4.13. Chemical properties of Mimi series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmol _c kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-22	5.7	0.2	0.37	0.08	1.60	2.10	0.19	0.08	4.07	0.35	4.42	92.08	7.65
22-40	6.0	0.2	0.29	0.05	1.34	1.90	0.14	0.06	3.44	0.15	3.59	95.82	1.04
40-58	6.1	0.2	0.22	0.04	2.40	1.50	0.27	0.11	4.28	0.15	4.43	96.61	0.48
58-114	5.9	0.2	0.07	0.01	2.94	2.20	0.14	0.08	5.36	0.13	5.49	97.63	0.32
114-165	6.0	0.2	0.04	0.01	2.14	1.90	0.21	0.08	4.33	0.15	4.48	96.65	0.24

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus.

4.1.14.2 Bulk density and porosity

The bulk density of Mimi series ranged from 1.4 to 1.6 Mg m⁻³ (Table 4.14). The highest was recorded in the fourth horizon (58 – 114 cm) while the lowest level (1.4 Mg m⁻³) was recorded in the surface horizon of the soil.

The levels of porosity of the soil ranged from 38.5 to 48.6% with the highest occurring in the surface horizon while the lowest occurred in the fourth horizon (58 – 114 cm) of the soil (Table 4.14).

4.1.14.3 Particle size distribution and texture

The sand fraction of the soil decreased with depth from 46.30 to 82.96% (Table 4.14). The results showed that clay and silt fractions of the soils tended to increase with depth from 4.30 to 26.40% and 12.74 to 21.30% respectively. The soil recorded loamy sand texture in the surface and subsurface horizons and sandy clay loam in the fourth and bottom horizons of the soil.

The general site information and profile description of Mimi series are presented in Table 13 and 14 (appendix 2). The profile of Mimi series is shown in Figure 4.7.

Table 4.14. Physical properties of Mimi series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand	Clay	Silt	
				(< 2 mm, %)			
0-22	0.40	1.36	48.6	82.96	12.74	4.30	ls
22-40	2.26	1.44	45.7	77.86	14.14	8.00	ls
40-58	5.95	1.39	47.6	66.22	17.38	16.40	sl
58-114	10.15	1.63	38.5	46.30	21.50	32.20	scl
114-165	12.96	1.61	39.3	52.30	21.30	26.40	scl

ls = Loamy sand, sl = Sandy loam, scl = Sandy clay loam

4.1.15 Chemical properties of Wenchi series

4.1.15.1 Soil pH and electrical conductivity

The pH (H₂O) of Wenchi series was 6.5 in the surface soil and 6.4 in the subsurface horizon.

The surface horizon recorded an EC of 0.6 dS m⁻¹ while the subsurface horizon had 0.3 dS m⁻¹ EC occurring in the bottom horizon of the soil (Table 4.15).

4.1.15.2 Organic carbon

The organic carbon content of the soil was 1.64% in the surface horizon, 1.42% in the subsurface horizon of the soil (Table 4.15).

4.1.15.3 Total nitrogen

The total nitrogen content of Wenchi series was 0.14% in the surface horizon and 0.11% in the subsurface horizon of the soil (Table 4.15).

4.1.15.4 Exchangeable bases

The levels of exchangeable bases in Wenchi series were high in the surface soil (Table 4.15).

The surface soil contained 4.81 cmol_c kg⁻¹ Ca, 2.50 cmol_c kg⁻¹ Mg, 0.26 cmol_c kg⁻¹ K and 0.11 cmol_c kg⁻¹ Na.

4.1.15.5 Exchangeable acidity

The exchangeable acidity content of the soil was low and same (0.10 cmol_c kg⁻¹) in the two horizons of the soil (Table 4.15).

4.1.15.6 Base saturation

Wenchi series had a base saturation of 98.71% in the surface horizon while the subsurface horizon had 98.12%.

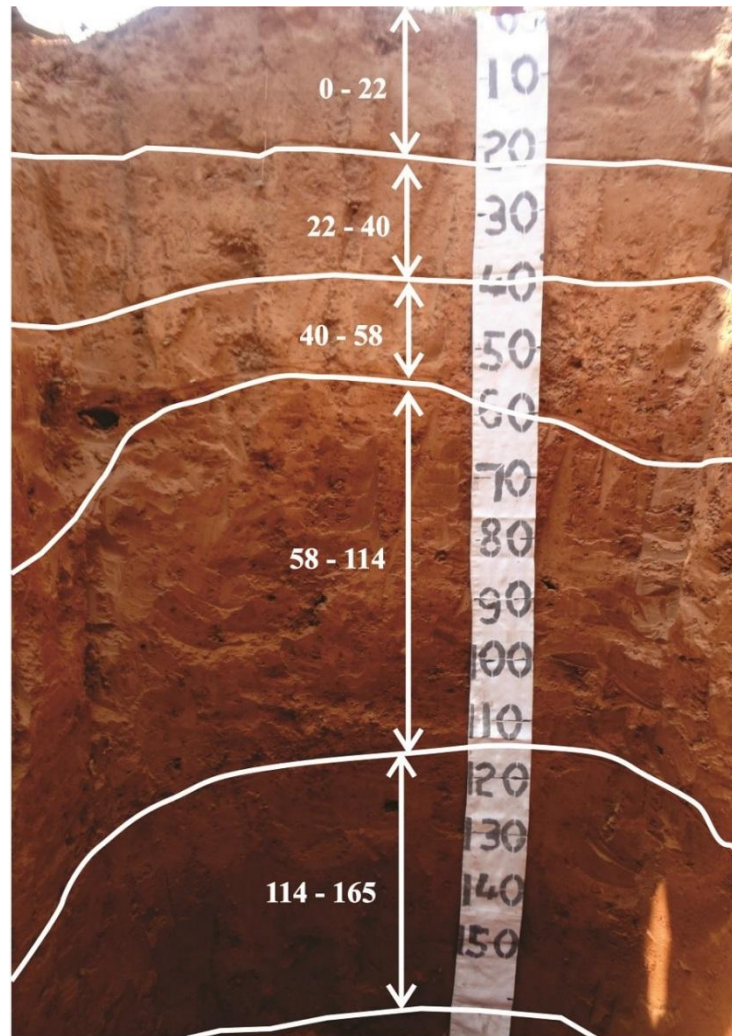


Figure 4.7. Profile of Mimi Series

4.1.15.7 Available phosphorus

The available phosphorus content of Wenchi series decreased with depth (Table 4.15). The level was 9.33 mg kg⁻¹ in the surface horizon and 2.47 mg kg⁻¹ in the subsurface horizon of the soil.

4.1.16 Physical properties of Wenchi series

4.1.16.1 Moisture content

The moisture content of Wenchi series was 5.20% in the subsurface horizon and 2.86% in the surface horizon (Table 4.16).

4.1.16.2 Bulk density and porosity

The bulk density of the soil was 1.7 Mg m^{-3} which occurred in the subsurface soil and 1.5 Mg m^{-3} in the surface horizon of the soil (Table 4.16). These levels of bulk density were high.

The porosity level was 43.20% in the surface soil and 35.73% in the subsurface horizon of the soil. (Table 4.16).

4.1.16.3 Particle size distribution and texture

The soil contained 50.32% sand, 41.38% silt and 8.30% clay in the surface soil of Wenchi series. In the subsurface horizon, the levels were 42.68% sand, 51.12% silt and 6.20% clay. The texture of the soil was loam in the surface soil and sandy loam in the subsurface soil.

The general site information and profile description of Wenchi series are presented in Table 15 and 16 (appendix 2). The profile of Wenchi series is shown in Figure 4.8.

Table 4.15. Chemical properties of Wenchi series

Depth (cm)	pH H ₂ O 1:1	EC (dS m ⁻¹)	Org. C — %	Tot. N —	Exchangeable Bases				T. E. B. (cmolc kg ⁻¹)	Ex. Ac.	ECEC	B. S. (%)	Avail. P (mg kg ⁻¹)
					Ca	Mg	K	Na					
0-14	6.5	0.56	1.64	0.14	4.81	2.50	0.26	0.11	7.68	0.10	7.78	98.71	9.33
14-29	6.4	0.30	1.42	0.11	3.20	1.70	0.24	0.08	5.22	0.10	5.32	98.12	2.47

EC = Electrical conductivity, Org. C = Organic carbon, Tot. N = Total nitrogen, Ex. Ac. = Exchangeable acidity

ECEC = Effective cation exchange capacity, Avail. P = Available phosphorus

Table 4.16. Physical properties of Wenchi series

Depth (cm)	Moisture Content %	Bulk Density (Mg m ⁻³)	Porosity %	Particle Size Distribution			Texture
				Sand ——	Silt (< 2 mm, %)	Clay ——	
0-14	2.86	1.51	43.2	50.32	41.38	8.30	l
14-29	5.2	1.70	35.73	42.68	51.12	6.20	sil

l = Loam, sil = Silty loam



Figure 4.8. Profile of Wenchi Series

CHAPTER FIVE

5.0 DISCUSSION

5.1 Evaluation of Soils and their Physical Environment for Maize Production

5.1.1 Soil Suitability Rating

Maize was used as the test crop in the suitability assessment. Three levels of suitability assessment were carried out; (1) soil evaluation (SQI) (2) DSSAT crop model and (3) multi-criteria evaluation. Several biophysical, climate and economic factors were used to assess the suitability of a given soil for maize production. These are discussed in detail in the following sections.

5.1.2. SQI Rating

5.1.2.1 Soil pH

Soil pH is an important variable which controls many chemical processes that take place in the soil ecosystem. Soil pH level or soil reaction gives an indication of conditions in the soil solution, particularly the availability or otherwise of both macro and micro–nutrient elements. The optimum pH range for most plants is between 5.5 and 7.0. As shown in Table 5.1, the pH of the soils ranged from moderately acidic (5.7) to slightly alkaline (7.5).

The subsoil 4 was slightly alkaline in two soils (7.5 and 7.2) with the highest (i.e. 7.5) occurring in Kupela series. Due to the fact that the pH of the soils ranged from moderately acidic to slightly alkaline, there would be no need to lime the soils for maize production. From the results (Table 5.1), the range of profile means and SE indicate that the pH values for Varempere, Lima, Mimi and Wenchi were not varied differently. On the contrary, while the pH of Kupela and

Kpelesawgu was significantly high, that of Ejura and Damongo was significantly low (Figure 5.1).

Spatial distributions of soil pH (maps) for each horizon used for the soil suitability assessment are shown in Figure 10 (see appendix 1).

Table 5.1. Distribution of pH in the soil profiles.

Horizons	Soil Series								Horizon Means	Min	Max
	pH										
	Var	Kup	Kpe	Lim	Eju	Dam	Mim	Wen			
Surface soil (8)	6.6	6.7	6.7	7.1	6.8	6.7	5.7	6.5	6.6	5.7	7.1
Subsoil 1 (8)	6.7	6.7	7.2	7.0	6.3	6.4	6.0	6.4	6.6	6.0	7.2
Subsoil 2 (7)	6.7	7.0	7.2	6.8	5.8	5.8	6.1		6.5	5.8	7.2
Subsoil 3 (6)	6.6	7.4		6.9	5.9	5.8	5.9		6.4	5.8	7.4
Subsoil 4 (5)		7.5		7.2	6.1	5.9	6.0		6.5	5.9	7.5
Subsoil 5 (2)				7.3		6.1			6.8	6.1	7.3
Profile means	6.7	7.1	7.0	7.1	6.2	6.1	5.9	6.4			
SE	0.03	0.17	0.17	0.08	0.18	0.15	0.07	0.05			

Values in parentheses represent number of samples, Var = Varempere, Kup = Kupela, Kpe = Kpelesawgu, Lim = Lima, Eju = Ejura, Dam = Damongo, Mim = Mimi, Wen = Wenchi, SE = standard error.

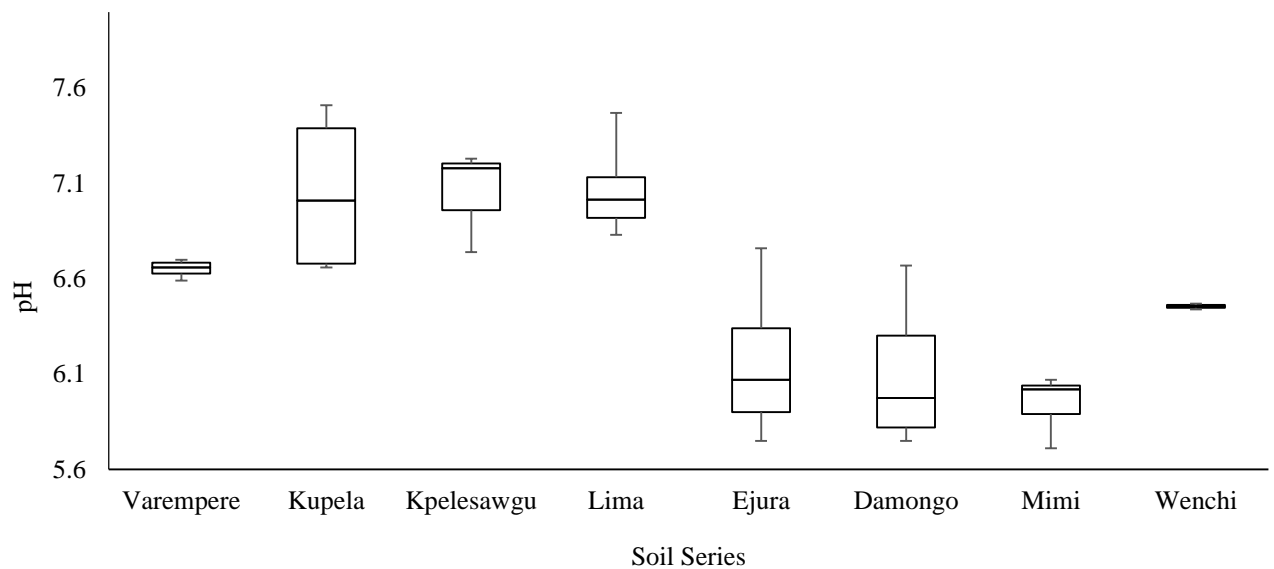


Figure 5.1. Box plot showing the average pH of the soils

5.1.2.2 Organic carbon (O.C)

The importance of organic carbon in enhancing soil physico-chemical and biological properties in soils cannot be over emphasized. Thus, cultural practices focused on arresting the decline and/or improving the level of organic matter would be recommended for soils and crop productivity. Unfortunately, organic matter content of soils are in continuous decline (Défossez, 2014). With the exception of fertilizers (inorganic or organic), organic matter provides the largest amount of macronutrients, especially N, P and K in soils (Don et al., 2011; Mtambanengwe, 2006).

Table 5.2 shows that the mean organic matter content of the surface soils was low (i.e. 1.31%). The individual values ranged from very low (< 0.06%) to moderate (2.83%). Apart from Wenchi and Kpelesawgu series which had moderate amounts of O.M. (2.83% and 2.55 respectively), all other soil series had low O.M. content ranging from 0.07 to 0.78% in the surface soil. O.M. contents of Kupela and Lima series were low and similar. The other soil series (i.e. Varempere,

Ejura and Damongo) had very low amounts of O.M. All the soils also generally showed decreased O.M. content with depth. Maps showing spatial distribution of O.M. are shown in Figure 11 (see appendix 1). The subsoil 1 of Wenchi series also had moderate amounts of O.M (i.e. 2.45%).

The standard errors (Table 5.2) show that Kpelesawgu and Wenchi series were varied in terms of O.C content. On the other hand, the other soils showed very little variation (0.04 – 0.09 SE) in its O.C dataset along the profile (i.e. based on the profile means and SE). Cultural practices such as cover crops could be used to improve the O.C content of the soils (Figure 5.2).

Table 5.2. Distribution of organic carbon in the horizons of studied site.

Horizons	Soil Series								Horizon Mean	Min	Max
	Var	Kup	Kpe	Lim	Eju	Dam	Mim	Wen			
Surface soil (8)	0.35	0.77	1.48	0.69	0.35	0.45	0.37	1.64	0.76	0.35	1.64
Subsoil 1 (8)	0.24	0.69	0.38	0.44	0.30	0.29	0.29	1.42	0.51	0.24	1.42
Subsoil 2 (7)	0.21	0.44	0.31	0.21	0.30	0.29	0.22		0.28	0.21	0.44
Subsoil 3 (6)	0.18	0.38		0.30	0.13	0.25	0.07		0.22	0.07	0.38
Subsoil 4 (5)		0.38		0.09	0.07	0.19	0.04		0.15	0.04	0.38
Subsoil 5 (2)				0.11		0.13			0.12	0.11	0.13
Profile Means	0.25	0.53	0.72	0.31	0.23	0.27	0.2	1.53			
SE	0.04	0.08	0.38	0.09	0.05	0.04	0.06	0.11			

Values in parentheses represent number of samples, Var = Varempere, Kup = Kupela, Kpe = Kpelesawgu, Lim = Lima, Eju = Ejura, Dam = Damongo, Mim = Mimi, Wen = Wenchi, SE = standard error.

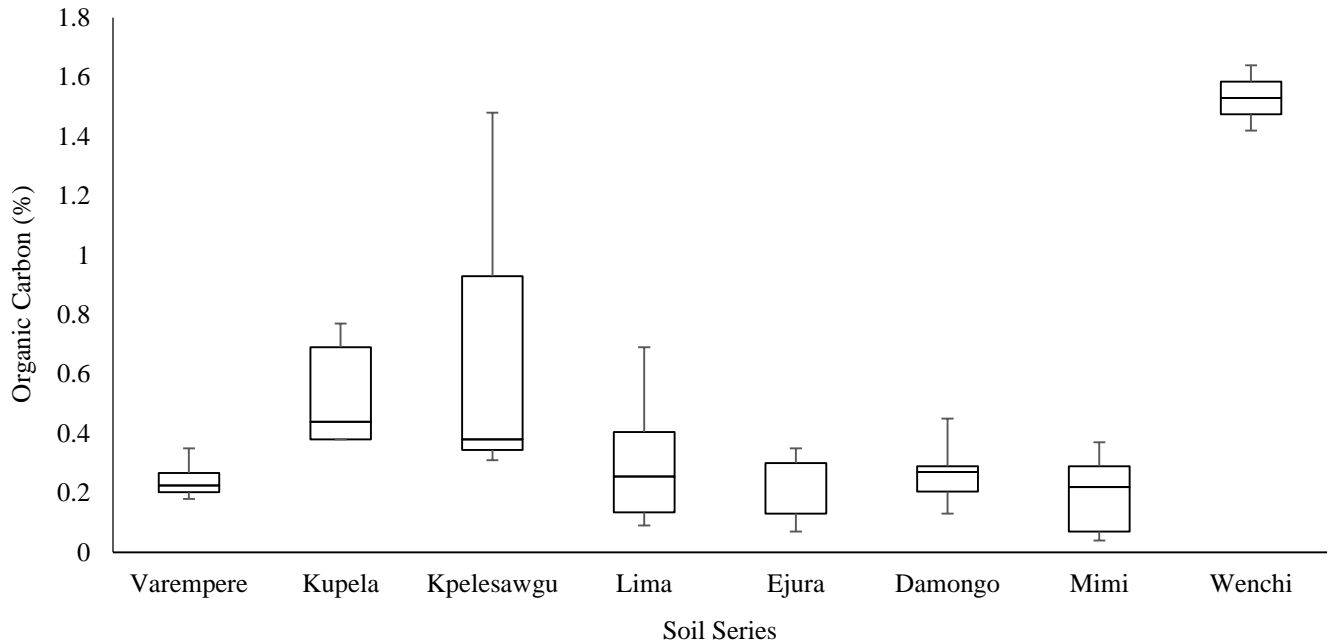


Figure 5.2. Box plot showing average organic carbon of the soils

5.1.2.3 Total nitrogen (%)

Total nitrogen levels in the surface soil layers ranged from low (0.08%) to moderate (0.17%) (Table 5.3). However, the total N levels were rated as moderate based on the mean total N value (0.11%) with the majority of the samples showing low levels but rated in the moderate rank based on the mean total N value (i.e. 0.11%) with the majority of the samples with low levels (i.e. < 0.1%). Just like O.M contents, the total N levels declined in all soils.

The total amount of N present in the soil is not readily available to crops. Thus, the low total N content of the soil samples would negatively affect soil and crop productivity. Figure 5.3 shows that Varempere and Wenchi series were symmetrical about the mean with depth.

Table 5.3. Distribution of Total N in the soil profiles.

Horizons	Soil Series								Horizon Mean	Min	Max
	Var	Kup	Kpe	Lim	Eju	Dam	Mim	Wen			
Surface soil (8)	0.08	0.14	0.17	0.12	0.08	0.08	0.08	0.14	0.11	0.08	0.17
Subsoil 1 (8)	0.05	0.11	0.06	0.09	0.06	0.06	0.05	0.11	0.07	0.05	0.11
Subsoil 2 (7)	0.05	0.08	0.05	0.04	0.06	0.05	0.04		0.05	0.04	0.08
Subsoil 3 (6)	0.02	0.07		0.05	0.03	0.05	0.01		0.04	0.01	0.07
Subsoil 4 (5)		0.04		0.01	0.03	0.02	0.01		0.02	0.01	0.04
Subsoil 5 (2)				0.02		0.02			0.02	0.02	0.02
Profile Means	0.05	0.09	0.09	0.06	0.05	0.05	0.04	0.13			
SE	0.01	0.02	0.04	0.02	0.01	0.01	0.01	0.02			

Values in parentheses represent number of samples, Var = Varempere, Kup = Kupela, Kpe = Kpelesawgu, Lim = Lima, Eju = Ejura, Dam = Damongo, Mim = Mimi, Wen = Wenchi, SE = standard error.

Total N contents just like organic carbon also varied except Wenchi series in the soil profiles. The maps of spatial distribution of total N are shown in Figure 9 (see appendix 1).

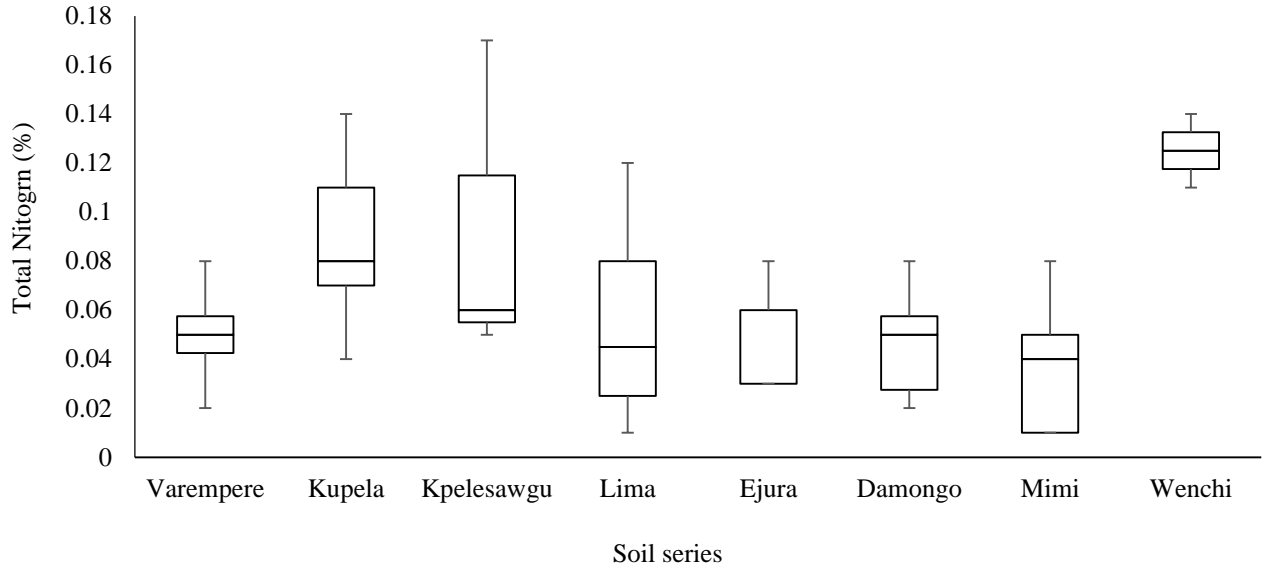


Figure 5.3. Box plot showing average Total N of the soils.

5.1.2.4 Effective cation exchange capacity (ECEC).

The ECEC of the soils was low (Table 5.4). The highest amount, 15.61 $\text{cmol}_c \text{kg}^{-1}$, occurred in the subsoil 2 of Kpelesawgu series. Cultural practices such as application of manure and compost, and soil conservation practices are recommended to be used to improve ECEC of the soils. The subsoil 2 of Kupela series had the lowest ECEC (1.58 $\text{cmol}_c \text{kg}^{-1}$) but also had the highest amount (8.90 $\text{cmol}_c \text{kg}^{-1}$) in the bottom horizon.

Generally, all the soils tended to have higher ECEC in the lower horizons probably due to leaching of cations from the horizons above. There was an accumulation of cations in bottom horizons which was beyond the rooting depth of most arable crops.

Table 5.4. Distribution of ECEC in the soil profiles

Horizons	Soil Series cmol _c kg ⁻¹								Horizon Mean	Min	Max
	Var	Kup	Kpe	Lim	Eju	Dam	Mim	Wen			
Surface soil (8)	2.37	4.09	4.38	5.57	3.07	4.92	4.42	7.78	4.58	2.37	7.78
Subsoil 1 (8)	2.39	3.94	5.41	3.51	4.43	2.57	3.59	5.32	3.90	2.39	5.41
Subsoil 2 (7)	3.78	1.58	15.61	3.00	5.04	3.31	4.43		5.25	1.58	15.61
Subsoil 3 (6)	4.10	3.14		4.32	6.56	3.37	5.49		4.5	3.14	6.56
Subsoil 4 (5)		8.90		5.83	6.27	5.46	4.48		6.19	4.48	8.90
Subsoil 5 (2)				7.64		4.82			6.23	4.82	7.64
Profile Means	3.16	4.33	8.47	4.98	5.07	4.08	4.48	6.55			
SE	0.46	1.23	3.58	0.70	0.64	0.47	0.30	1.23			

Values in parentheses represent number of samples, Var = Varempere, Kup = Kupela, Kpe = Kpelesawgu, Lim = Lima, Eju = Ejura, Dam = Damongo, Mim = Mimi, Wen = Wenchi, SE = standard error.

The ECEC of the soils varied as shown by the profile means (Table 5.4 and Figure 5.4). However, the ECEC of the Kpelesawgu series deviated so much (SE of 3.58) from its profile mean. Kpelesawgu series was highly positively skewed whilst Kupela series exhibit the opposite. Damongo and Wenchi series showed symmetrical distribution (Figure 5.4).

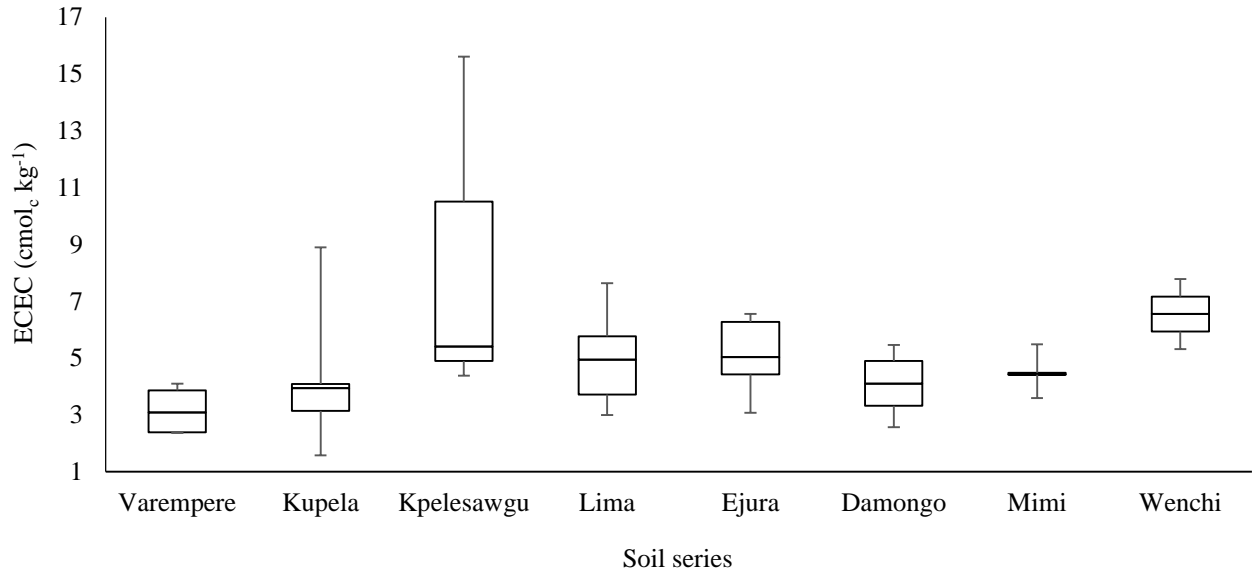


Figure 5.4. Box plot showing average ECEC of the soils.

Varemperre, Kupela, Kpelesawgu, Lima, Ejura and Damongo series varied whilst the other soils did not (Figure 5.4). Maps showing spatial distribution of ECEC are shown in Figure 12 (see appendix 1).

5.1.2.5 Available phosphorus

The available phosphorus levels in the soils were generally rated low ($< 10 \text{ mg kg}^{-1}$) and tended to decline with soil depth (Table 5.5). The highest amounts of available P occurred in the surface soil of Wenchi series (9.33 mg kg^{-1}), Mimi series (7.65 mg kg^{-1}) and Varemperre series (7.41 mg kg^{-1}).

Table 5.5. Distribution of Available phosphorus in the soil profiles.

Horizons	Soil Series mg kg ⁻¹								Horizon Mean	Min	Max
	Var	Kup	Kpe	Lim	Eju	Dam	Mim	Wen			
Surface soil (8)	7.41	1.20	1.99	4.86	4.62	4.94	7.65	9.33	5.25	1.20	9.33
Subsoil 1 (8)	2.15	0.40	1.91	3.11	1.99	2.31	1.04	2.47	1.92	0.40	3.11
Subsoil 2 (7)	2.31	0.72	1.44	1.67	1.36	1.83	0.48		1.40	0.48	2.31
Subsoil 3 (6)	0.08	0.88		1.28	0.24	0.80	0.32		0.60	0.08	1.28
Subsoil 4 (5)		1.20		0.96	0.80	0.16	0.24		0.67	0.16	1.20
Subsoil 5 (2)				1.12		0.24			0.68	0.24	1.12
Profile Means	2.99	0.88	1.78	2.17	1.80	1.71	1.95	5.90			
SE	1.56	0.15	0.17	0.63	0.76	0.73	1.43	3.43			

Values in parentheses represent number of samples, Var = Varempere, Kup = Kupela, Kpe = Kpelesawgu, Lim = Lima, Eju = Ejura, Dam = Damongo, Mim = Mimi, Wen = Wenchi, SE = standard error.

Wenchi series with the highest amount of available phosphorus showed symmetrical distribution about the mean (Figure 5.5). The distribution of available P was not significantly variable in Kpelesawgu series unlike it was in the other soils. Maps showing spatial distribution of available P in the soils are shown in Figure 13 (see appendix 1).

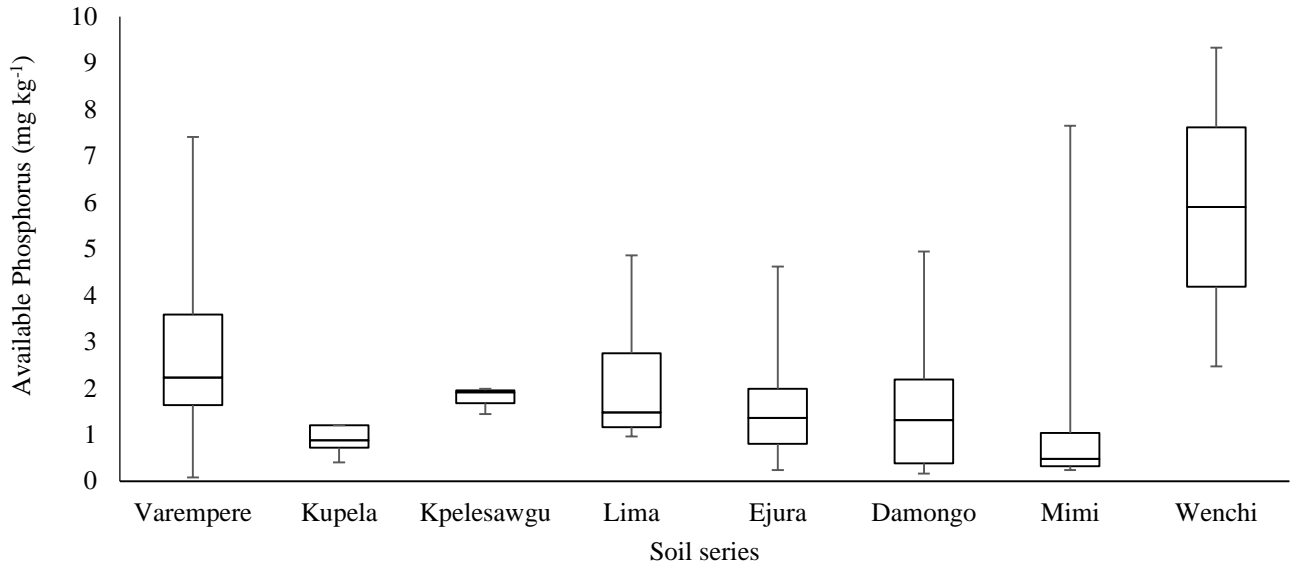


Figure 5.5. Box plot showing average available phosphorus of the soils.

5.1.2.6 Physical soil quality indicators

Knowledge on soil depth is important to evaluate the potential and appropriate utilization of the soil for crop cultivation because the depth of a soil and its capacity for water and nutrients often determine crop yield (Jarmer, et al, 2009). As indicated by Jenny (1994), every soil series has its own vertical distribution pattern and depth function. Lower soil profile depths measured ranged from 29 cm indicating a very shallow soil (Wenchi series) to > 160 cm representing a very deep soil (Mimi series). With the exception of Wenchi series (the non-suitable soil depth classification for maize cultivation) 87.5% of the soils had highly suitable maize cultivation classification.

Estimated water use efficiency for irrigated and rainfed crop production systems is about 50% moisture content (Wallace, 2000). All the soils in this study had low moisture content, below the 50% threshold. The low moisture contents might be due to, among others, the relatively high bulk densities of the soils (Tables 7 to 21).

Varempere series had lower moisture content (0.54%) in its surface horizon than in the lower horizons. The porosity of Varempere series increased with depth probably as a result of the texture of the soil (i.e. loamy sand at the surface and sandy loam at the bottom). The sandy loam horizon might not have held high amounts of coarse fragments, hence larger pores and much water.

Kupela series had a relatively higher bulk density (1.48 to 1.89 Mg m⁻³) which could restrict root penetration. The sandy texture of Kupela series would make it poor in water retention. Thus, Kupela series could have poor water holding capacity.

Kpelesawgu series, a loamy textured soil, had a moderate to high bulk density ranging from 1.44 to 1.68 Mg m⁻³ partly contributing to the low moisture content (3.42 to 7.7%) of the soil.

Lima series had a relatively high bulk density (1.84 Mg m⁻³) in the bottom horizon and low moisture content (0.66%). It also had loam texture. The high bulk density, in particular would impede root penetration.

Ejura series had larger-size but fewer pores with lower water holding capability which made it have a low moisture content. The texture of the soil was sandy loam except at the depth of 85 to 113 cm which was sandy clay loam and had a moisture content of 20.2%.

Damongo series had the highest moisture content (13.13%) probably due to its high clay content. The texture of its horizons ranged from sandy loam to sandy clay loam. The pore spaces also decreased from the top to the bottom of the soil with increasing bulk density.

The clay and moisture contents of Mimi series increased with depth. Thus, the increasing clay content of the horizons might have partly contributed to the increasing moisture content with depth.

Wenchi series with a loam topsoil and a silty loam subsoil showed decreasing clay content with depth. But, its bulk density increased with depth.

Mimi series had the highest moisture content of 19.04% while Varemperere series recorded the lowest of 1.00%. Ejura series had the highest bulk density while Mimi had the lowest. Kpelesawgu had the highest porosity of 58.97% while Damongo had the lowest of 33.84%.

Generally, all the horizons of the soils had low moisture content, small pore space and high bulk densities.

Using the soil indicators, thresholds, interpretations and scores on each soil series physico-chemical and morphological parameters for crop growth as given in Chapter 4 and in Table 5.6 below, the SQI values for each soil was obtained as summarized in Table 5.7. Based on the discussions above, it could be deduced that the moderately suitable soils for maize production include Damongo, Ejura and Mimi series. These soils are deep, well to moderately well drained with sandy loam in the surface soils, sandy clay loam to loam textured subsoils and sandy clay textures in their bottom horizons. Their limitation was the texture of the surface and subsoils. These textures showed low porosity (< 30%) in the subsoils and high porosity (> 50%) in the surface soil (i.e. Damongo series). Thus, it would be important to have the surface of these soils

covered with vegetation, mulch or crops stubbles so as to improve their water-holding capacity and reduce leaching. The marginally suitable soils include Varempere, Kupela, Kpelesawgu and Lima series (Table 17, see appendix 2).

Table 5.6. Soil Indicator, Thresholds, Interpretation and Scores.

Indicators	Range	Interpretation	Score
pH	5.5 - 7.2	Slightly acidic to neutral: Optimum for plant growth	2
	>7.2 <8.0	Slightly to moderately alkaline: Preferred by some plants, possible P and some metal deficiencies	1
N (%)	0.2 - 0.3	Moderate limitation	1
	>0.3	Slight to no limitation	2
SOC (%)	2 - 3	Moderate limitation	1
	>3.0	Slight to no limitation	2
WHC (cm)	<5.0	Water-stress to plants	0
	5 – 10	Moderate water availability	1
	>10	Good water capacity for plants	2
Available P (mg kg ⁻¹)	<10	Low	0
	10 – 20	Moderate	1
	>20	High	2
BD (g cm ⁻³)	<1.0	High organic soil, supports plant roots	2
	1.0 - 1.5	Adverse effects unlikely	1
	>1.5	Adverse effects likely	0

BD: bulk density, N: nitrogen, SOC: soil organic carbon, AWC: available water capacity. Modified from Mukherjee and Lal (2014).

Table 5.7. Calculated Soil Quality Index (SQI) from Measured Soil Properties.

Soil Series	BD- Score	pH- Score	SOC- Score	TN- Score	Av-P- Score	WHC- Score	SQI	SQI*100	Rank
Vampere	1	1.67	0.04	0	0.28	0.66	3.64	36.4	7
Kupela	0.64	1.59	0.19	0	0.08	1.17	3.67	36.71	5
Kpelesawgu	1	1.59	0.29	0	0.17	0.34	3.38	33.84	8
Lima	0.54	1.58	0.07	0	0.2	1.26	3.66	36.62	6
Ejura	0.46	1.64	0.03	0	0.17	1.91	4.21	42.11	4
Damongo	1	1.62	0.05	0	0.16	1.93	4.76	47.63	2
Mimi	1	1.58	0.01	0	0.18	1.69	4.46	44.61	3
Wenchi	1	1.68	0.68	0.13	0.51	0.95	4.94	49.39	1

BD= bulk density, SOC = soil organic carbon; TN = total nitrogen; Av-P = available phosphorus WHC = water holding capacity.

These soils were moderately well drained (Varempere series), imperfectly to poorly drained (Kupela series), moderately well to imperfectly drained (Kpelesawgu series) and poorly drained (Lima series). They were predominantly loamy sand, sandy loam or loamy textured and quickly dried up at the onset of the dry season. The limitations of these soils were partly due to the presence of coarse fragments (stones and concretions), poor soil structure, and poor drainage.

Although Kpelesawgu, Varempere and Kupela soil series contained moderate to abundant amounts of gravel and concretions, with adequate rainfall and good distribution, they would be able to sustain the growth of maize. It was observed in the field that farms were commonly cultivated on these marginally suitable soils. Therefore, it would be important that excess water is drained off these soils during the initial growth stage of maize. Furthermore, cultural practices geared towards reducing erosion such as incorporating crop residues and stubbles into the soils should be encouraged.

Based on the results of the study, Wenchi series was found to be unsuitable for maize cultivation (Table 17, see appendix 2). Wenchi series had a loamy surface soil and a silty loam subsoil. The limitation of the soil was mainly the high amount of coarse fragments it contained. It contained 77.77% gravel in the surface soil and 84.38% in the subsoil. In addition to the high amounts of coarse fragments, Wenchi series was also very shallow (effective depth of about 29 cm). These two factors namely high amounts of coarse fragments and shallowness made Wenchi series marginally suitable for maize cultivation. Irrigation would be very important for Wenchi series because of its excessive drainage characteristics. Furthermore, ploughing this soil should be regulated so as not to expose the underlying massive ferruginous solid ironpan beneath the shallow surface soil. Although Wenchi series could support cereals and groundnut, crop residue

retention and incorporation should be encouraged. Also, cultural practices geared towards reducing soil erosion should be recommended.

The order of ranking of the soils for their suitability for maize production is Damongo > Kupela > Mimi > Varempere > Lima > Ejura > Wenchi > Kpelesawgu.

5.1.3 Soil Suitability based on DSSAT model

The Decision Support System for Agrotechnology Transfer (DSSAT) cereal (Maize) V4.5 experimental model calibrated for Ghanaian ‘Obaatampa’ maize (Hoogenboom et al., 2004) was adopted for the estimation of yield (i.e. harvest weight at maturity – HWAM) of all the soils studied. Climatic data covering 1980 to 2010 (Ghana Meteorological Service, 2010) were used in the simulation with 2 fertilizer treatments. The fertilizer treatments adopted were: (1) no fertilization (T1) and (2) fertilization (T2) based on MoFA recommended rates of NPK (60 – 40 – 40) (MoFA, 2011).

Chapoto et al. (2013) stated that the reintroduction of fertilizer subsidy has led to increase in general fertilizer use and intensity among farmers. This implies that maize yield could improve with appropriate soil management interventions.

Table 5.8 shows the simulated maize yields for a 30 year duration. The simulation outputs indicated that the individual soils had the potential to improve maize production if appropriate soil management interventions were adopted.

In view of this, coefficient of variation (CV) was used to normalize the dispersion of each soil series yield and also to indicate how yields were spatially varied among the eight soil series

(Table 5.8). According to Cambardella et al. (1994) and Wilding (1985), CV's less than 15% indicates low spatial variability, 15-35%, moderate and >35%, high spatial variability.

Soils in the Interior Savannah agro-ecological zones were generally spatially variable ranging from 28 (moderate; Mimi series) to 131% (high; Varempere series) whilst in the Forest-Transition, Lima series had the lowest CV of 7% with the highest (59%) occurring in Damongo series indicating a low to high spatial variability respectively. Comparing the soils in the two agro-ecological zones, soils in the forest-transition exhibited lower variability (7 – 59%) than those in the interior savanna agro-ecological zone (i.e. 28 – 131%).

In the Interior Savannah (Northern Region: Mimi, Verempere, Kpelesawgu and Kupela) agro-ecological zone, Kupela series (Gbogdaa community) had the highest mean yield (3.391.5 kg ha⁻¹) with the lowest (774.5 kg ha⁻¹) occurring in Varempere series (Nahari community). Similarly, Mimi series (Naniik community) had a mean yield higher than Kpelesawgu series (Famisa community) in the interior savannah agro-ecological zone (Table 5.8). Unlike the soils of the Forest-Transition agro-ecological zone (Brong Ahafo Region: Wenchi, Ejura, Damongo and Lima), Wenchi series (Kwayasi-Yeji community) had the lowest mean yield of 550 kg ha⁻¹ with the highest (3,901 kg ha⁻¹) occurring at Alhassan Kura (Lima series). Amongst the two agro-ecological zones, Wenchi series recorded the lowest mean yield whilst Lima series recorded the highest.

Table 5.8. Simulated maize yields for the various soil series

Soil Series	Mean Yield	Simulated Yields		SD	CV (%)
		Min	Max		
		(T1)	(T2)		
kg/ha					
Varempere	774.5	58	1491	1013.28	131
Kupela	3391.5	2701	4082	976.51	29
Kpelesawgu	1511	481	2541	1456.64	96
Lima	3901	3707	4095	274.36	7
Ejura	2675.5	1778	3573	1269.26	47
Damongo	2224	1293	3155	1316.63	59
Mimi	3375	2712	4038	937.62	28
Wenchi	550	200	800	252	49

From the physico-chemical point of view, simulated maize yields on Wenchi series was the lowest possibly due to impedance to root growth (presence of underlained ironpan) and low WHC (37.2%). Varempere and Kpelesawgu series also showed some impedance to root growth. The high gravel contents of Kpelesawgu series (87%), Wenchi series (70%) and Varempere series (65%) made them excessively well-drained and thus poor in nutrient holding capability. As shown in Figure 5.6, simulated maize yields under fertilizer application (i.e. T2) generally showed increased maize yields in all the soil series assessed.

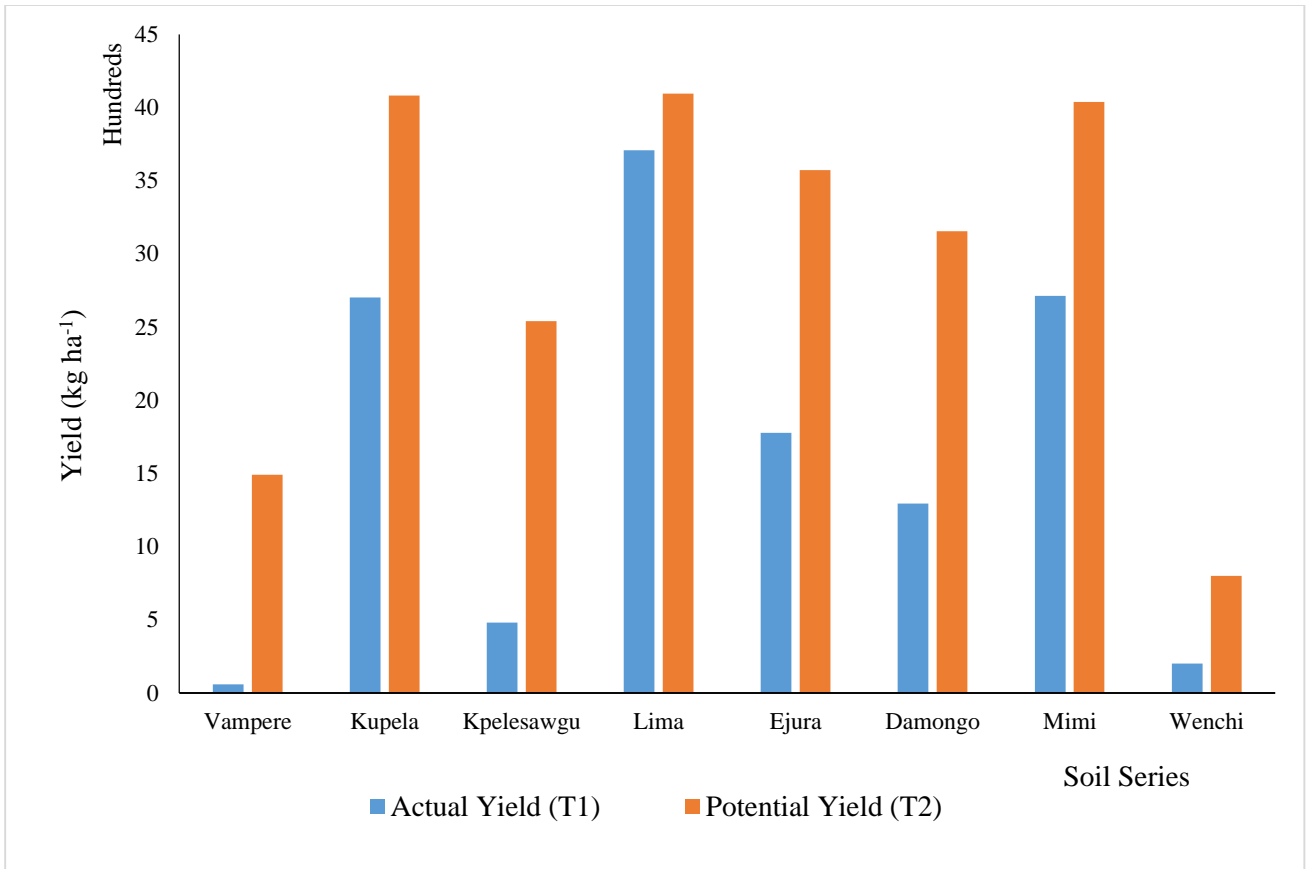


Figure 5.6. DSSAT simulated yields of all soil series

Under T2, the DSSAT model simulated an increase yield of 1,433 kg ha⁻¹ in Vampere series, 1,381 kg ha⁻¹ (Kupela series), 2,060 kg ha⁻¹ (Kpelesawgu series), 1,326 kg ha⁻¹ (Mimi series), 1,862 kg ha⁻¹ (Damongo series), 600 kg ha⁻¹ (Wenchi series) and 1,795 kg ha⁻¹ yield in Ejura series. Of all the increase in yield recorded, Lima series recorded the lowest of 388 kg ha⁻¹. This might have partly contributed by its sandy loam nature, low spatial variability (CV of 7%) and WHC of 52.4 mm. This partly explains why the lowest percentage yield increase of 110% was recorded in Lima series (Figure 5.7). Damongo series which recorded the highest WHC of 99.75% did not obtain the highest yield increase, partly due to its low ECEC content throughout the profile. On the other hand, Vampere series recorded the highest yield increase of 2,570%

(Figure 5.7), which indicates that fertilizer application can significantly improve maize cultivation and yields.

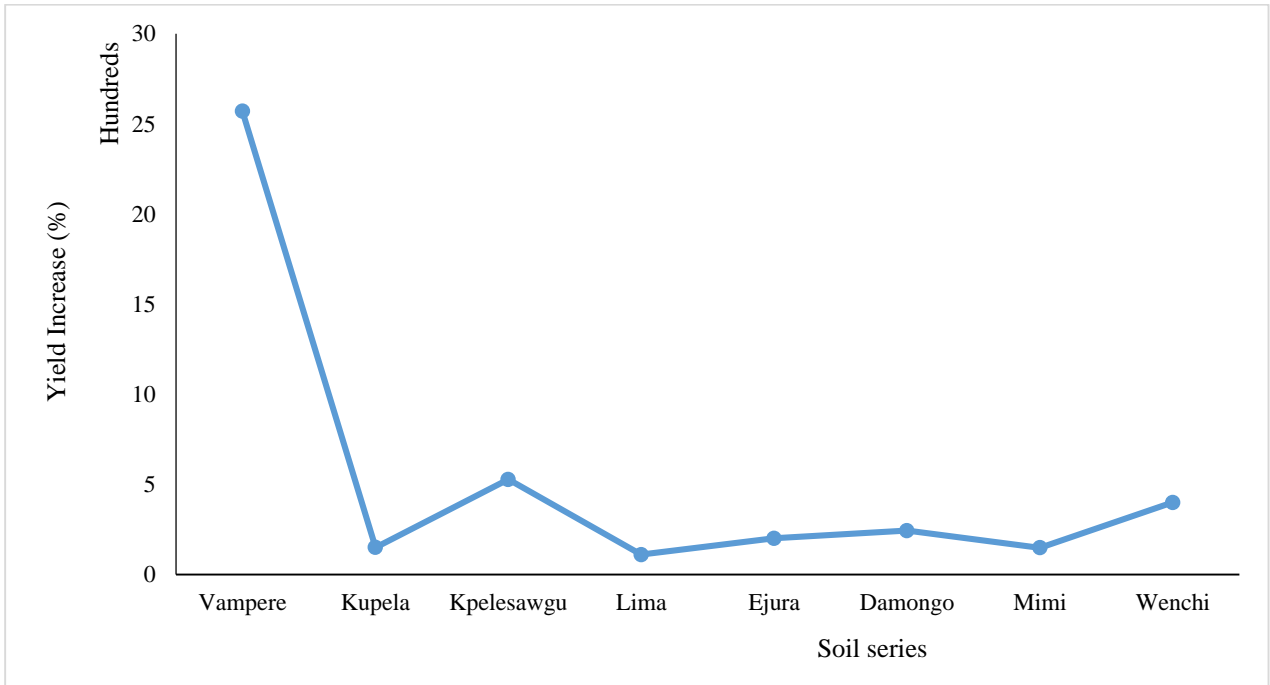


Figure 5.7. Percentage Yield Increase from T1 to T2.

The bulk density of Wenchi series ranged from 1.5 to 1.70 Mg m⁻³. According to Ruark et al. (1982) and Adjadeh (1989), soil bulk density > 1.65 Mg m⁻³ restricts root growth and is associated with poor nutrient uptake as shown by the low yield for Wenchi series. The high sand contents of Wenchi (50.32%) and Vampere series (80.80%) partly influenced leaching of plant nutrients and loss of moisture.

Although Damongo, Ejura and Mimi series were developed from the same parent material (i.e. sandstone), they showed different levels of yield even under T1. Damongo series had 1,293 kg ha⁻¹ yield, Ejura series 1,778 kg ha⁻¹ yield and Mimi series 2,712 kg ha⁻¹ yield. This change in yield was partly attributed by different management practice adopted by farmers in the areas.

At Nannik community (Mimi series) good conservation practices (e.g. residue retaining) were adopted as compared to Lailai (Ejura series) and Shafa – Wiase Zongo (Damongo series) communities.

Lima and Kupela series were found on the lower to bottom slope of the catena. Consequently, they might have received alluvial materials which showed high moisture retention capacities and high O.M content. Relatively, these provided favourable conditions which probably contributed to the relatively higher yields of maize on these soils. Lima series had 3,707 kg ha⁻¹ yield and Kupela series had 2,701 kg ha⁻¹ under T1 (Figure 5.6). Due to their high moisture retention capacities (Lima series; WHC of 52.4 mm and Kupela, 47.6 mm), they were likely to show low susceptibility to drought.

The gaps between the actual (unfertilized treatments (T1)) and the potential (fertilized treatments (T2)) yield showed that Kpelesawgu series was the most responsive to fertilizer application (Figure 5.8). Kpelesawgu recorded 2,060 kg ha⁻¹ with the lowest (388 kg ha⁻¹) occurring in Lima series. This was followed in the order Damongo > Ejura > Varempere > Kupela > Mimi > Wenchi > Lima.

From Figure 5.7 and 5.8, Varempere series appears to be more responsive to fertilizer application than Kpelesawgu but in terms of yield it is more economically viable to cultivate maize on Kpelesawgu series than Varempere series.

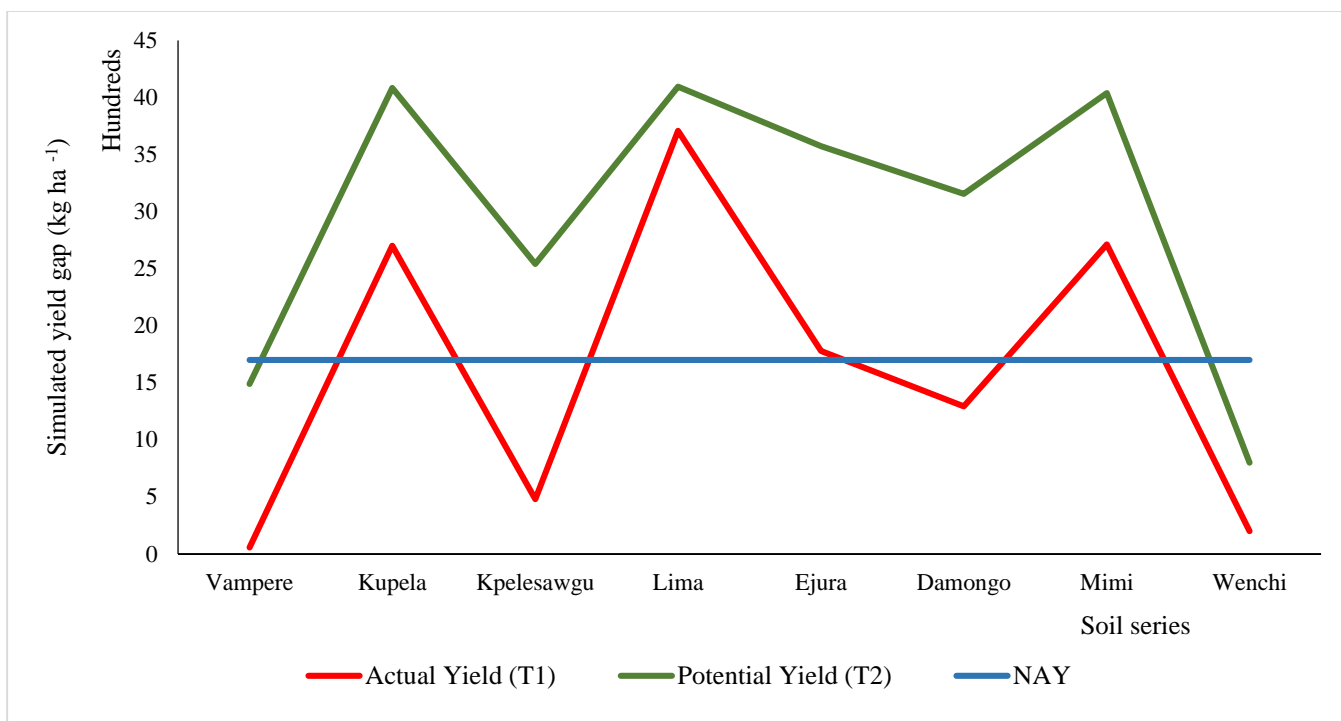


Figure 5.8. Chart showing percentage gap of yield increase in kg ha⁻¹ of each soil series.

Comparing all the eight soil series, Figure 5.8 indicates that it is not economically viable to apply fertilizer to Lima and Wenchi series at every cropping season, however, it would require periodic fertilization so as to prevent total mining of soil nutrients.

Improving crop production with appropriate management intervention is important when matters arise on closing up the gap of maize yields as against the national average yield (NAY) of 1,700 kg ha⁻¹ (SRID, 2011). Under T1 Vampere, Kpelesawgu, Wenchi and Damongo series had yields below the NAY (Figure 5.8). On the other hand, Kupela, Mimi, Lima and Ejura series had higher yields than the NAY.

Though the yield of Kpelesawgu and Damongo series were below the NAY under T1, fertilization (T2), greatly improved the yield potential of these soils. Nevertheless, their response to fertilization was moderate series (Kpelesawgu; 528 and Damongo series; 244%) as

compared to Varempere series (2,570%). However, response to fertilization reflected in their yield potentials. Under T2, yields on these soils increased from 481 to 2,541 kg ha⁻¹ in Kpelesawgu series and 1,293 to 3,155 kg ha⁻¹ in Damongo series, thus above the NAY. This indicates that, maize cultivation on these dominant soils could improve maize production in Ghana.

The main factor contributing to the gaps in yield (kg ha⁻¹) (i.e. below and above the NAY) was partly the effectiveness of crop management practices e.g. fertilizer and residue management. It would be important to record climatic data at the sampling sites so as to have improved simulation outputs.

5.1.4 Multi-criteria evaluation of soil series alternatives

Making appropriate soil management decision in crop production suggests the need to consider multiple factors and aspects of agriculture that affects the returns a small holder farmer could make from his/her harvest as income. For instance a smallholder famer finds his/her income more important whilst an agronomist might find the factors that contribute to improve crop yield more important. As such, to successfully blend these defined set of criteria (Table 18, see appendix 2) the alternative soil management strategies were evaluated by the MCA (Table 5.9).

Table 5.9. MCA ranking of the suitability of soil series.

Region	Soil Series Alternatives	MCA Rating Score							
		Revenue	Fertilizer cost	SQI-score	Labour cost	MCR	Conservation practice	Fournier Index	Distance to Market
	Ejura	1	1	0.85	1	-0.77	0.33	1	0.04
Brong	Damongo	0.63	1	0.96	1	-0.4	0.33	1	1
Ahafo	Wenchi	0.19	1	1	1	-1	1	1	0.25
	Lima	0.46	1	0.74	1	-0.56	0.67	0.81	0.04
	Kpelesawgu	0.23	1	0.68	0.94	-0.72	-0.33	0.98	0.08
Northern	Varempere	0.24	1	0.74	0.94	-0.27	0.33	0.79	0.01
Region	Kupela	0.23	1	0.74	0.94	-0.34	-0.33	0.79	0.11
	Mimi	0.44	1	0.9	0.94	-0.15	1	0.98	0.08

Units of measure; Revenue = (yield (kg ha⁻¹) * price), Fertilizer cost = (no. of bags (kg ha⁻¹) * price), Labour cost = GH¢, Distance to market = (1/d²), d = distance (km²), MCR = soil erodibility

Fertilizer cost, soil erodibility, labour cost and conservation practices were considered as cost to the farmer because these affects crop performance and yield whilst revenue, SQI-score, forunier index and distance to market were considered as benefits to farmers. In terms of financial returns, Ejura series recorded the highest of 3,120 GH¢ with the lowest (600 GH¢) occurring in Wenchi series. With the support from the Government of Ghana, fertilizer cost was equal (363.76 GH¢) for all areas. However, labour cost was location specific, it ranged from 717.75 GH¢ in the Brong Ahafo region to 677.75 in the Northern Region.

Wenchi series recorded the highest soil erodibility (0.98) with the lowest (0.15) occurring in Mimi series. Conservation practices (residue retaining) partly affected the performance of crops. It was highly practices on Wenchi series Mimi series. These two recorded the highest score of 30. But at Famisa (on Kpelesawgu series) and Gbogdaa communities (on Kupela series), these practices were not rampant hence a score of (-10). Of all the alternative soil series, Varempere was the most near to the market center. The other series are in the order; Lima and Ejura > Kpelesawgu and Mimi > Kupela > Wenchi > Damongo.

Figure 5.9 and 5.10 shows the MCA outcome and overall ranking of each criteria in relation to each soil series. From Figure 39, MCA results generally were ranked higher in the Forest Transition agro-ecological zone (Brong Ahafo) than those of the Guinea Savanna agro-ecological zone (Northern Region). Lower MCR of soils of the Guinea Savanna agro-ecological zone might have partly be contributed by the generally flat terrains of the area as compared to the undulating terrains of the Forest Transition agro-ecological zone (Figure 1 to 8, see appendix 1). Conservation practices were rated higher in the Forest Transition agro-ecological zone than the Guinea Savanna agro-ecological zone. This also was partly contributed by livestock grazing in the Guinea Savanna agro-ecological zone. This affected the performance in the MCA.

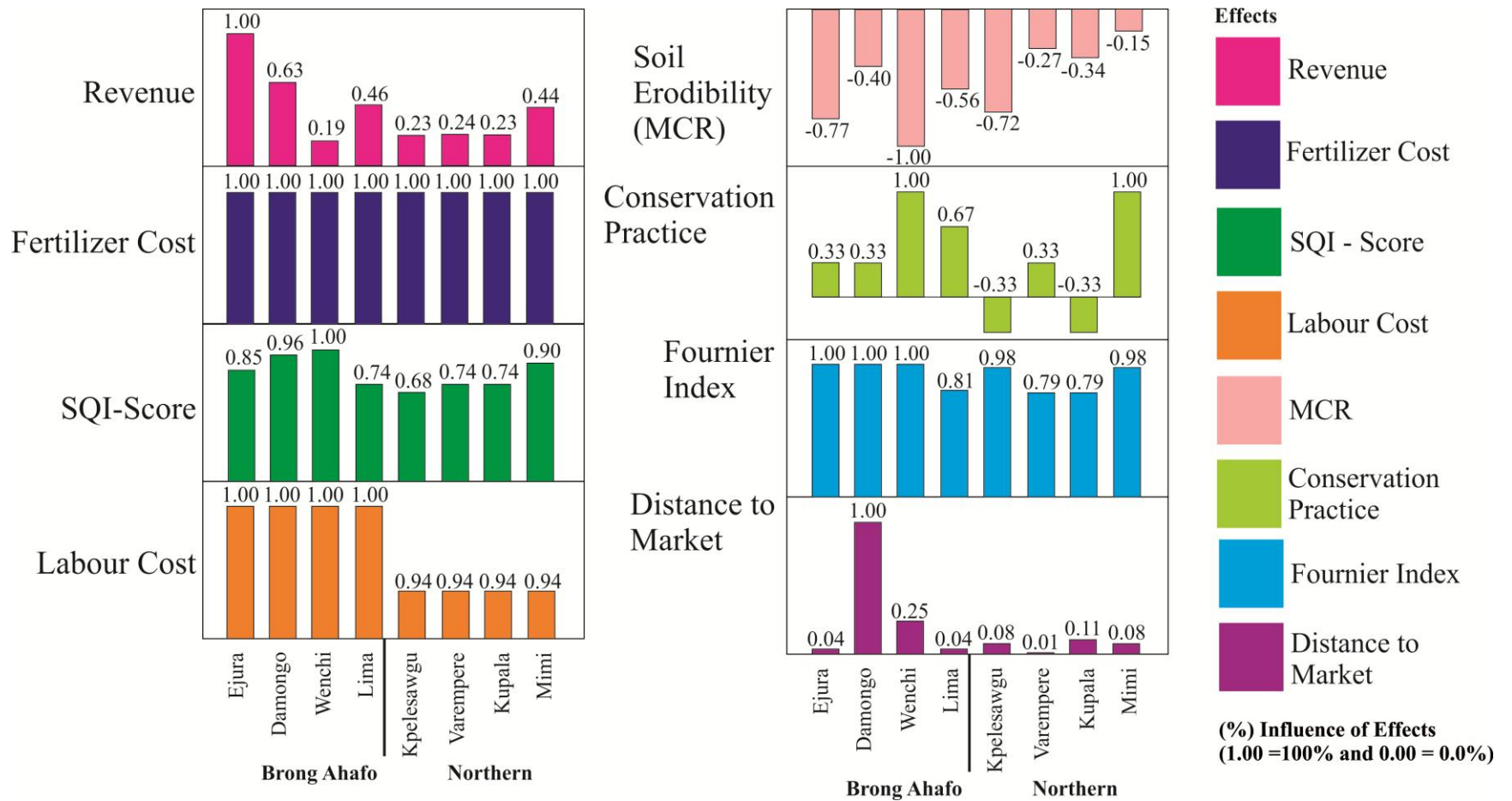


Figure 5.9. Criteria scores for the different soils.

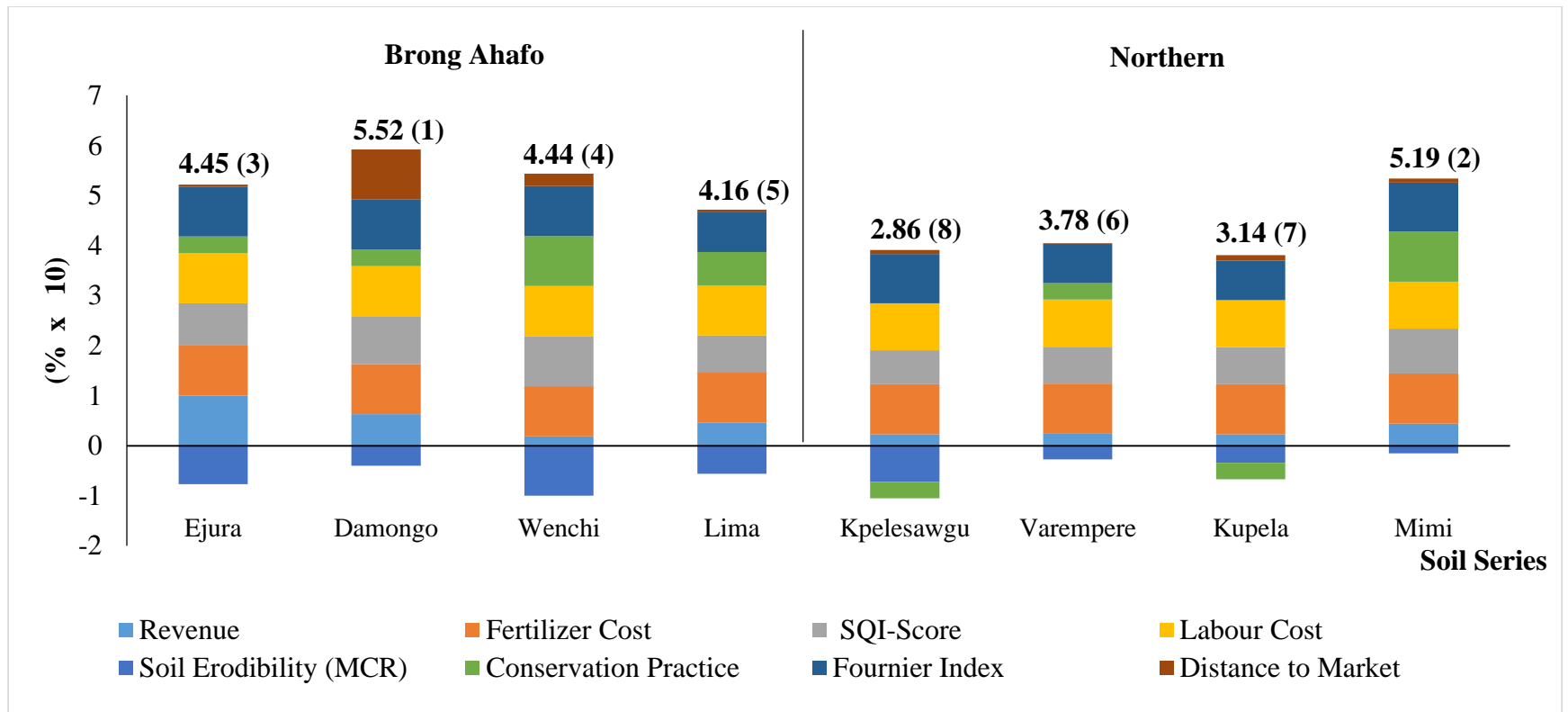


Figure 5.10. Ranked soil alternatives

As shown in Fig 5.10, a simple and straight forward MCA was carried out, ranking was sensitive to the influence of each criterion applied. Beyond soil limitations, the outcomes of the overall ranking was significantly affected by fertilizer and labour cost. Moreover, the impact of rainfall on associated runoff (from sheet and rill erosion) estimated by the Fournier index also affected the MCA outcome. This result was partly due to the relatively higher rainfall in the Forest Transition agro-ecological zone (Brong Ahafo) than the Guinea Savanna agro-ecological zone (Northern Region).

Damongo series was ranked the highest (with an overall score of 5.52) in terms of maize productivity under different soil management options. This was followed by the others in the order; Mimi (5.19) > Ejura (4.45) > Wenchi (4.44) > Lima (4.16) > Varempere (3.78) > Kupela (3.14) > Kpelesawgu (2.86). It must be emphasize that these overall scores are site dependent (i.e. the study location). It has been identified that each criterion is important in decision making process (the criterion and soil series) (Janssen and Herwijnen, 2007).

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

From the results of this study, the following conclusions and recommendations are made;

6.1 Conclusions

1. Generally, Damongo series could be ranked “best” among the soils. It was best in the MCA and SQI rankings. Based on all the rankings, Damongo, Mimi, Lima and Ejura soil series could be considered suitable for maize intensification. The other soils namely Kpelesawgu, Kupela, Varempere and Wenchi could be considered as marginal for maize intensification.
2. Results of the study showed that there are more suitable maize production zones in the forest-savanna transition (Brong Ahafo) than in the guinea savanna (Northern Region) zone of Ghana.
3. To decide on the appropriate soil management options in crop production, there is the need to consider multiple factors including those that affect the returns of a farmer. From the results of the study, the MCA relative to the FAO ratings and DSSAT yield simulations gave more desirable outcomes. Nevertheless, the FAO ratings and the DSSAT yield simulation should not be ignored rather they should be included in the MCA. Since each approach led to a different ranking of the soil series, the study recommends the use of MCA rather than the FAO ratings in identifying alternative management possibilities. Furthermore, the importance of MCA which enables effective and efficient decision making cannot be overemphasized. Also, farmers

preferences should be considered in the decision making process in comparison to the traditional FAO soil suitability rating for soil management.

6.2 Recommendations

1. Although MCA considers factors beyond soil limitations, the FAO suitability ratings should not be disregarded. Rather, the FAO suitability ratings should be used as the basis for evaluating and designing the MCA criteria.
2. Site specific weather data and field trials are recommended for the improvement and validation of MCA outcomes.
3. The soils (Varempere, Kpelesawgu and Wenchi series) which showed low maize productivity without fertilizer application need surface drainage and maintenance of surface cover with vegetation or crop stubbles so as to reduce erosion and improve their water-holding capacity.
4. Addition of compost, manure and other sources of organic matter would help increase the overall productivity of the concretionary soils (Wenchi, Varempere and Kpelesawgu series).
5. Wenchi series should be left under grass for rough grazing of livestock as an alternative livelihood for farmers since in its current state it cannot effectively support maize cultivation.
6. Due to the hazards of soil erosion, moisture loss and drying of the surface horizons of Damongo, Lima, Ejura, Kupela and Mimi series, drainage channels and other water control measures should be improved at the onset and during wet seasons.

7. Fertilizer application, especially N and P fertilizers, is recommended for the soils for productive cultivation of maize.

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APPENDIX

Appendix 1

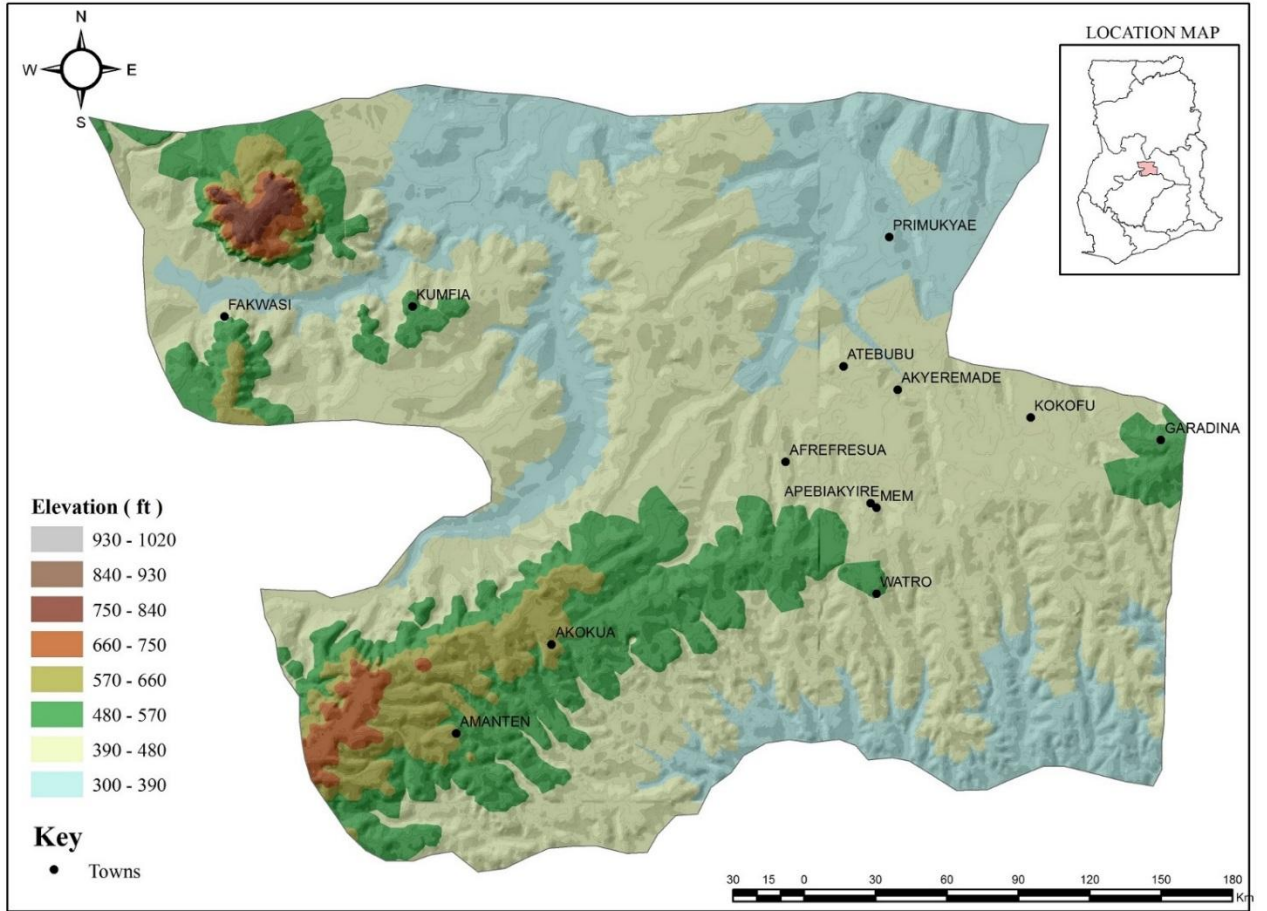


Figure 1. Relief and Drainage of Atebubu District

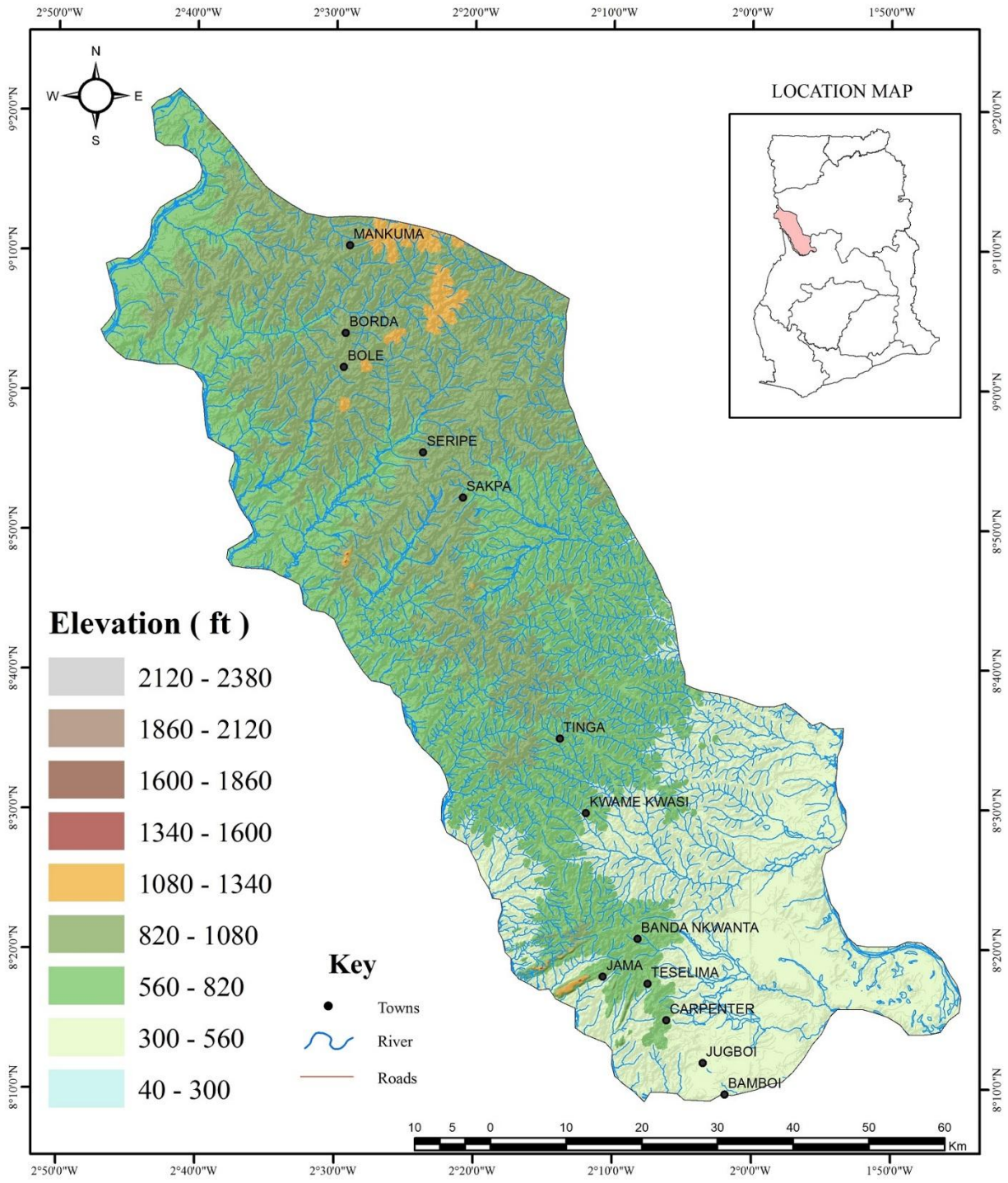


Figure 2. Relief and Drainage of Bole District

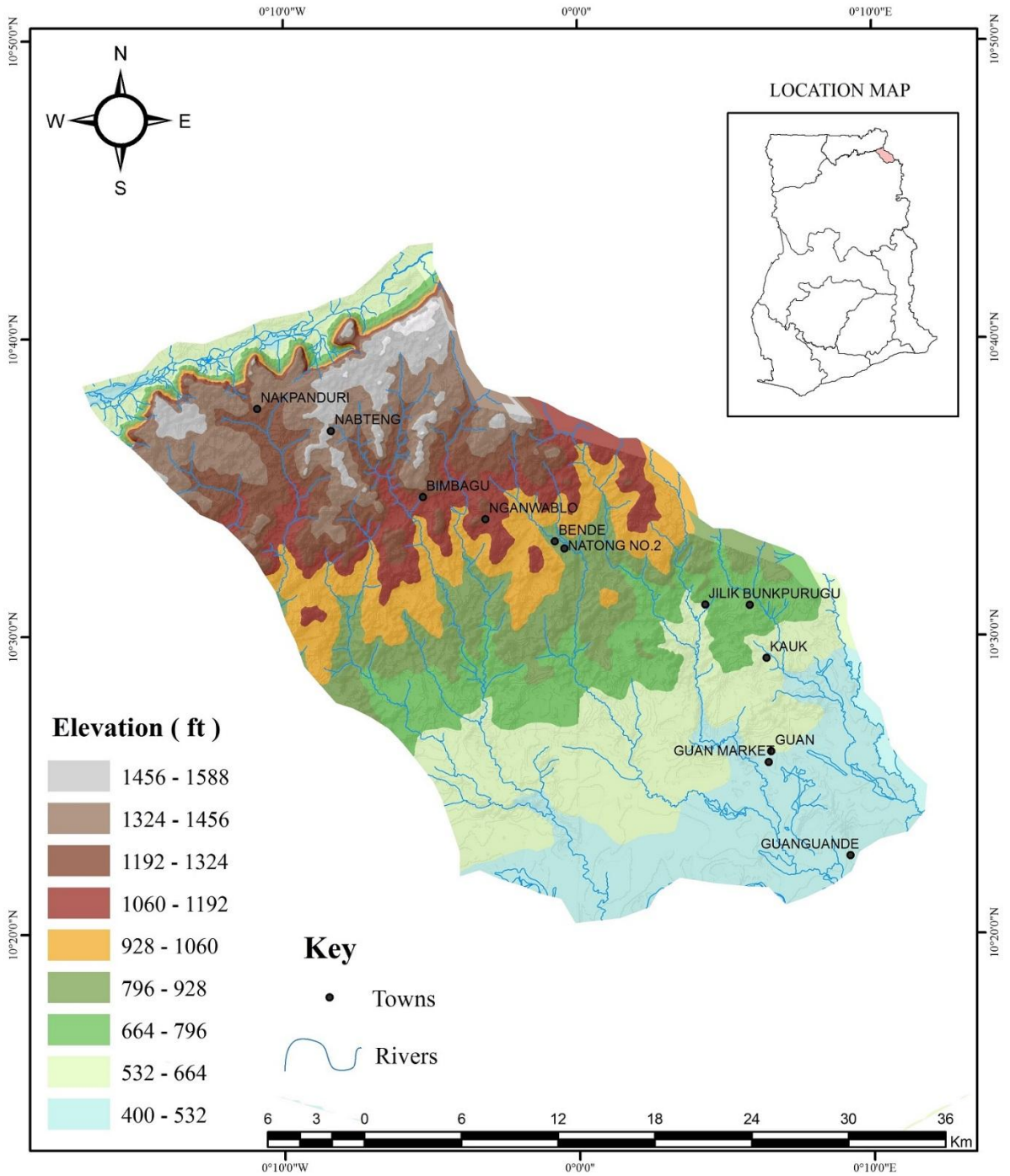


Figure 3. Relief and Drainage of Bunkprugu-Yunyoo District

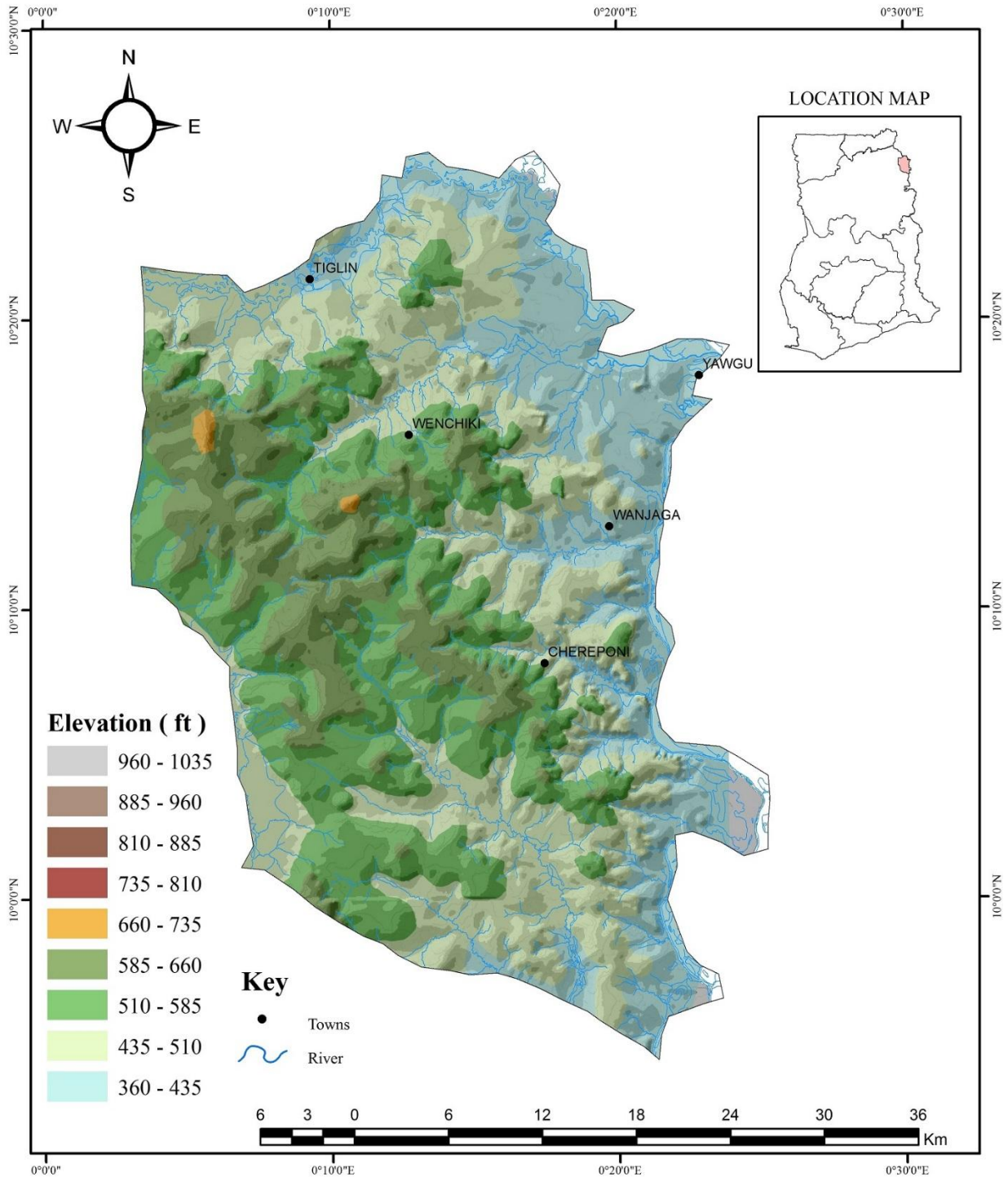


Figure 4. Relief and Drainage of Chereponi District

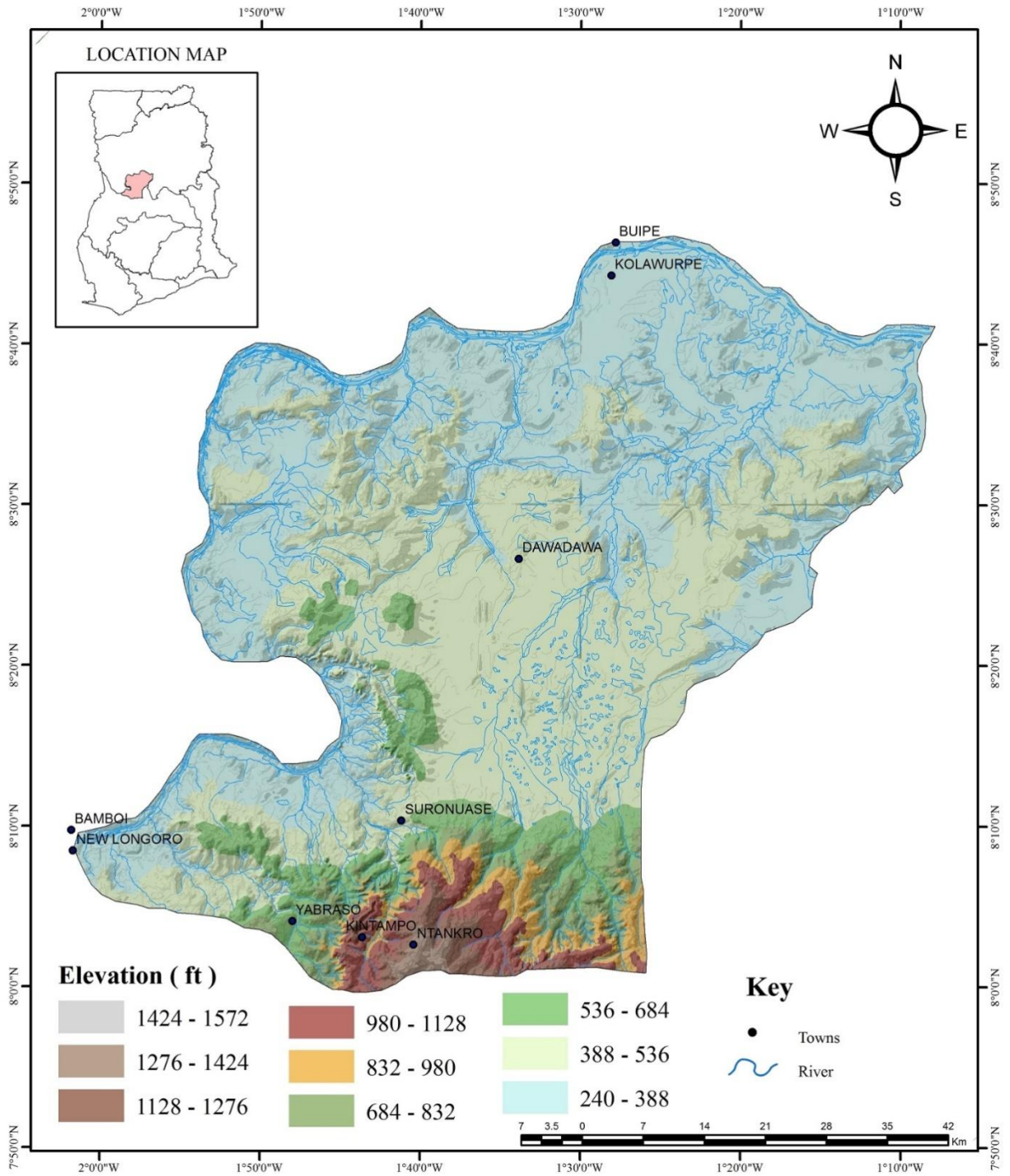


Figure 5. Relief and Drainage of Kintampo-North District

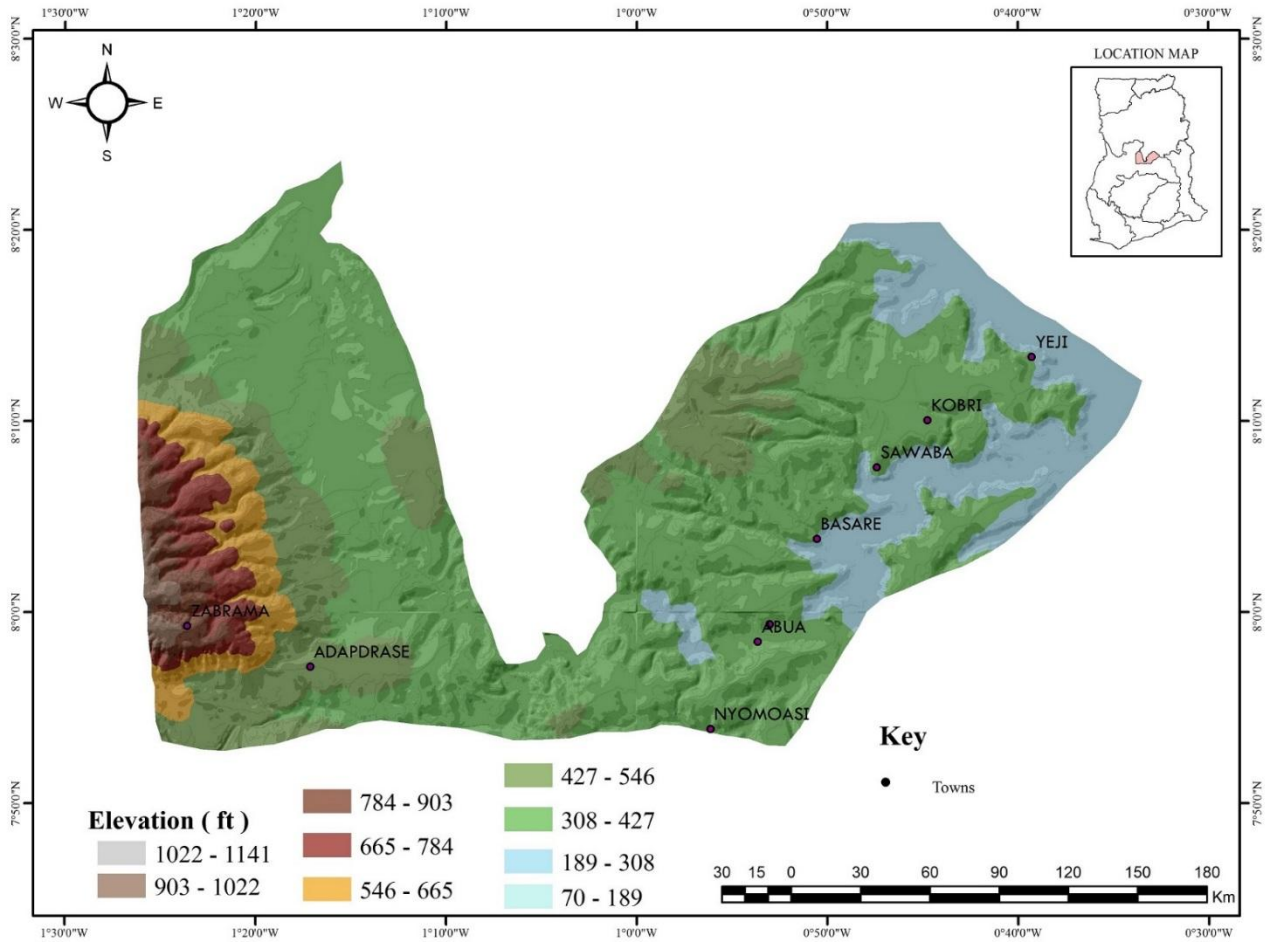


Figure 6. Relief and Drainage of Pru District

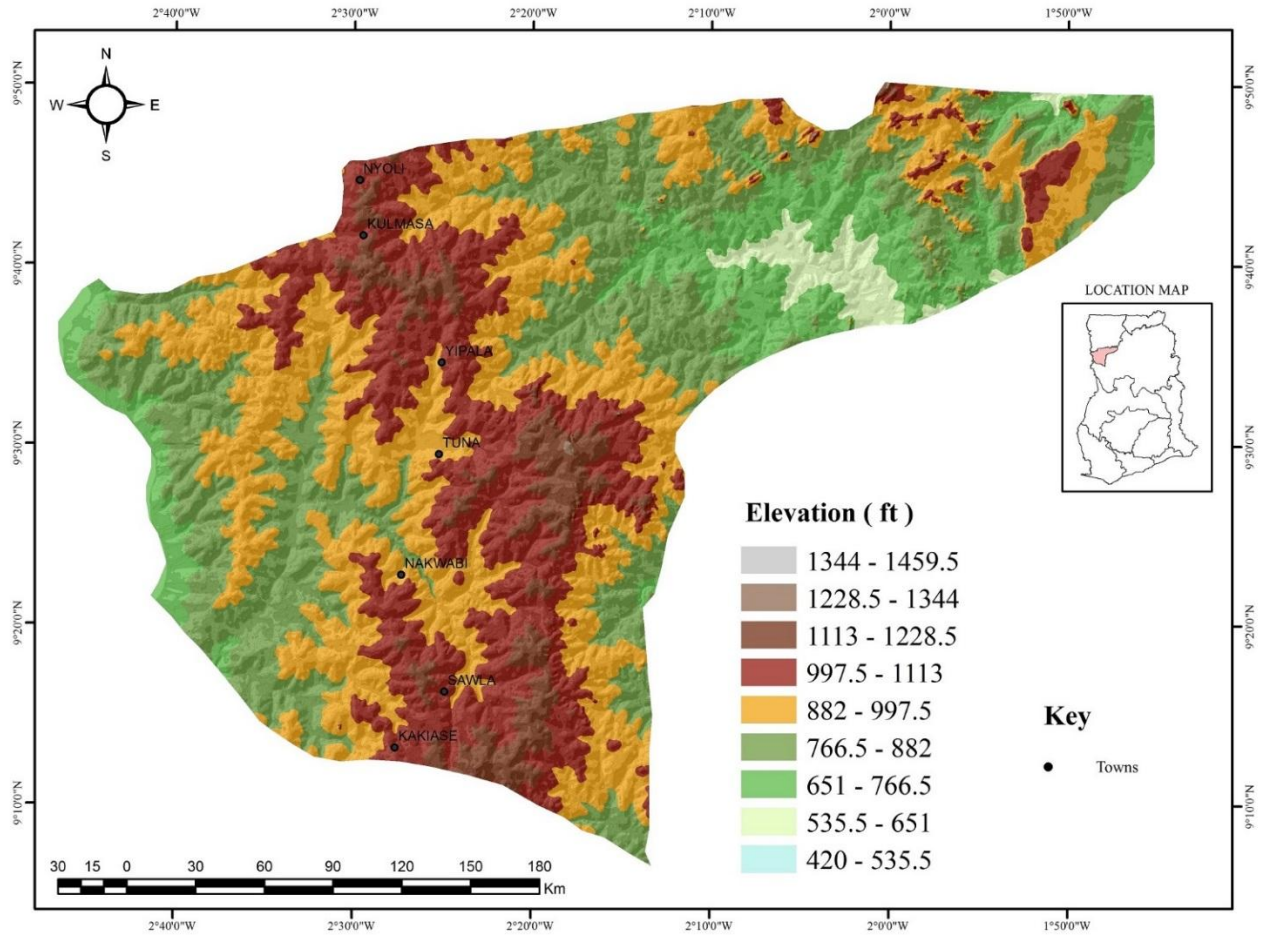


Figure 7. Relief and Drainage of Sawla-Tuna-Kalba District

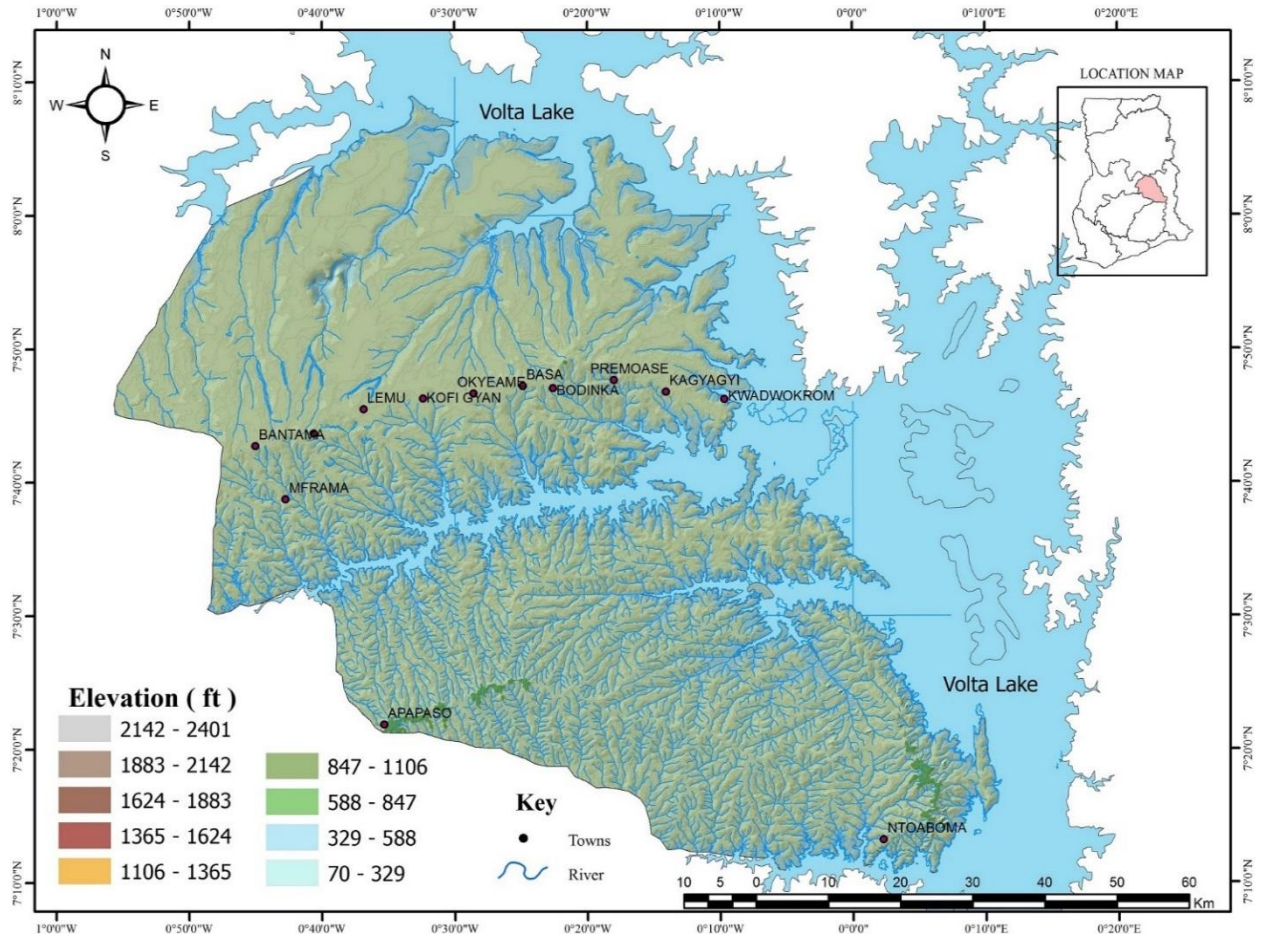


Figure 8. Relief and Drainage of Sene District

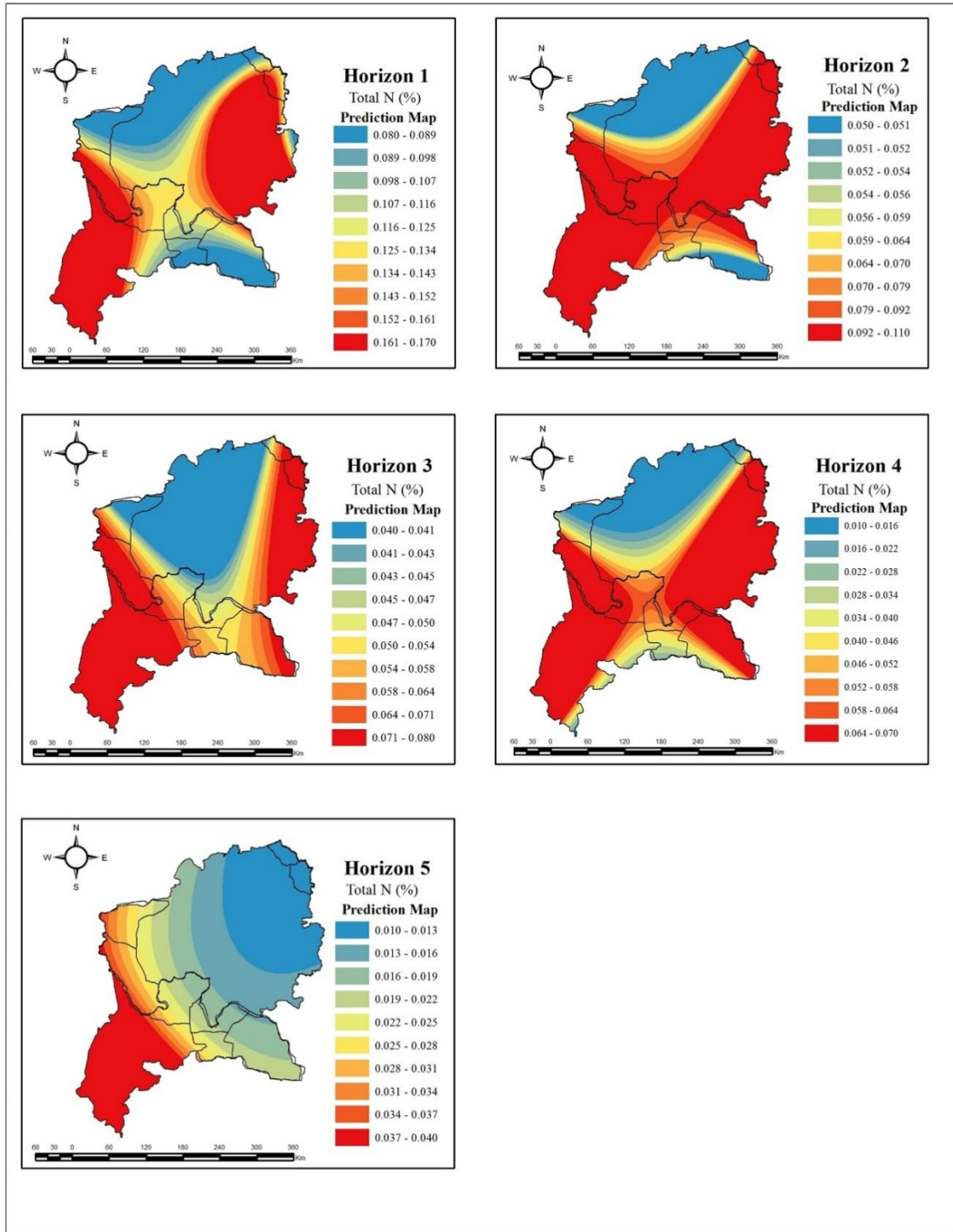


Figure 9. Spatial distribution of soil Total N used for soil suitability assessment

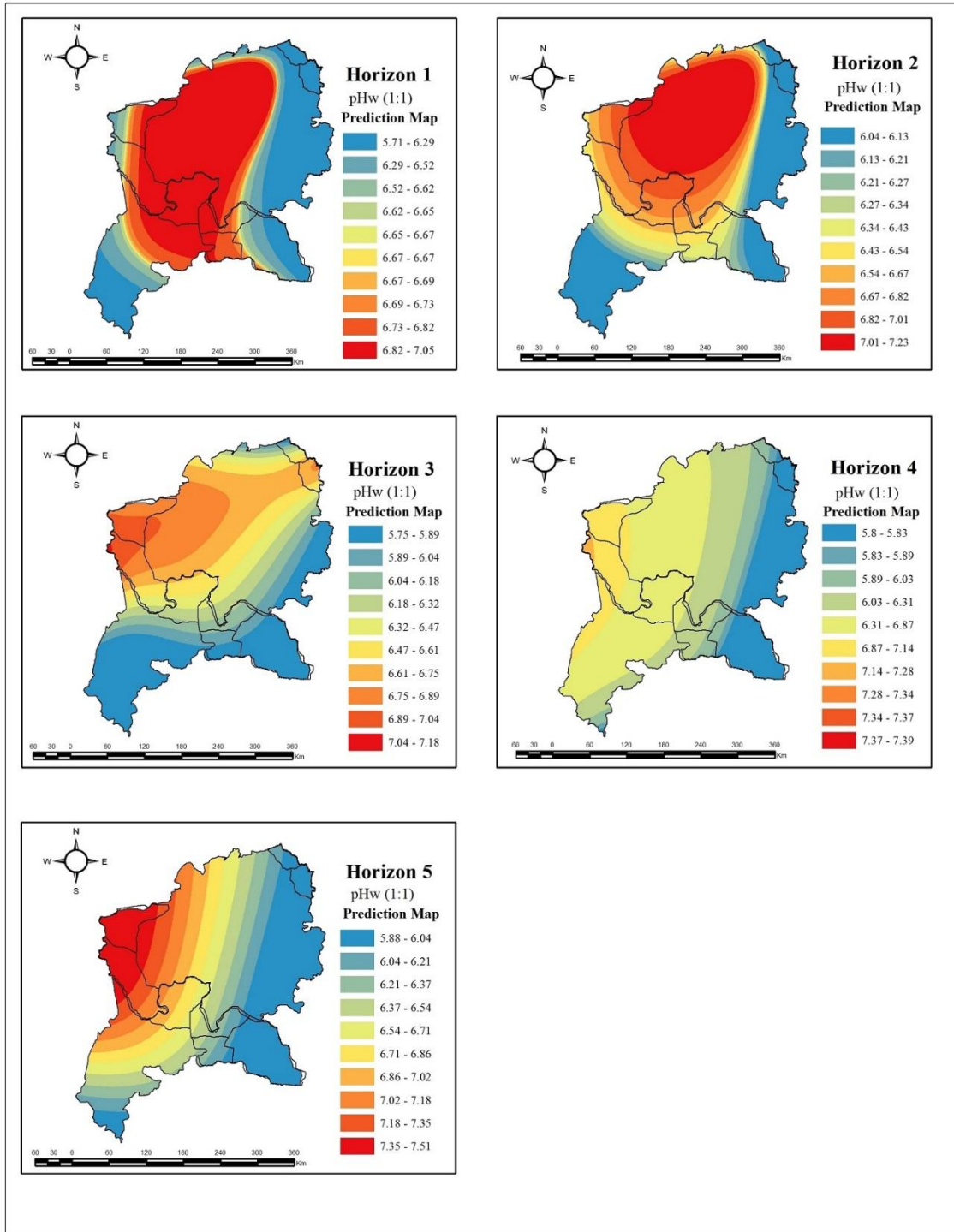


Figure 10. Spatial distribution of soil pH used for soil suitability assessment

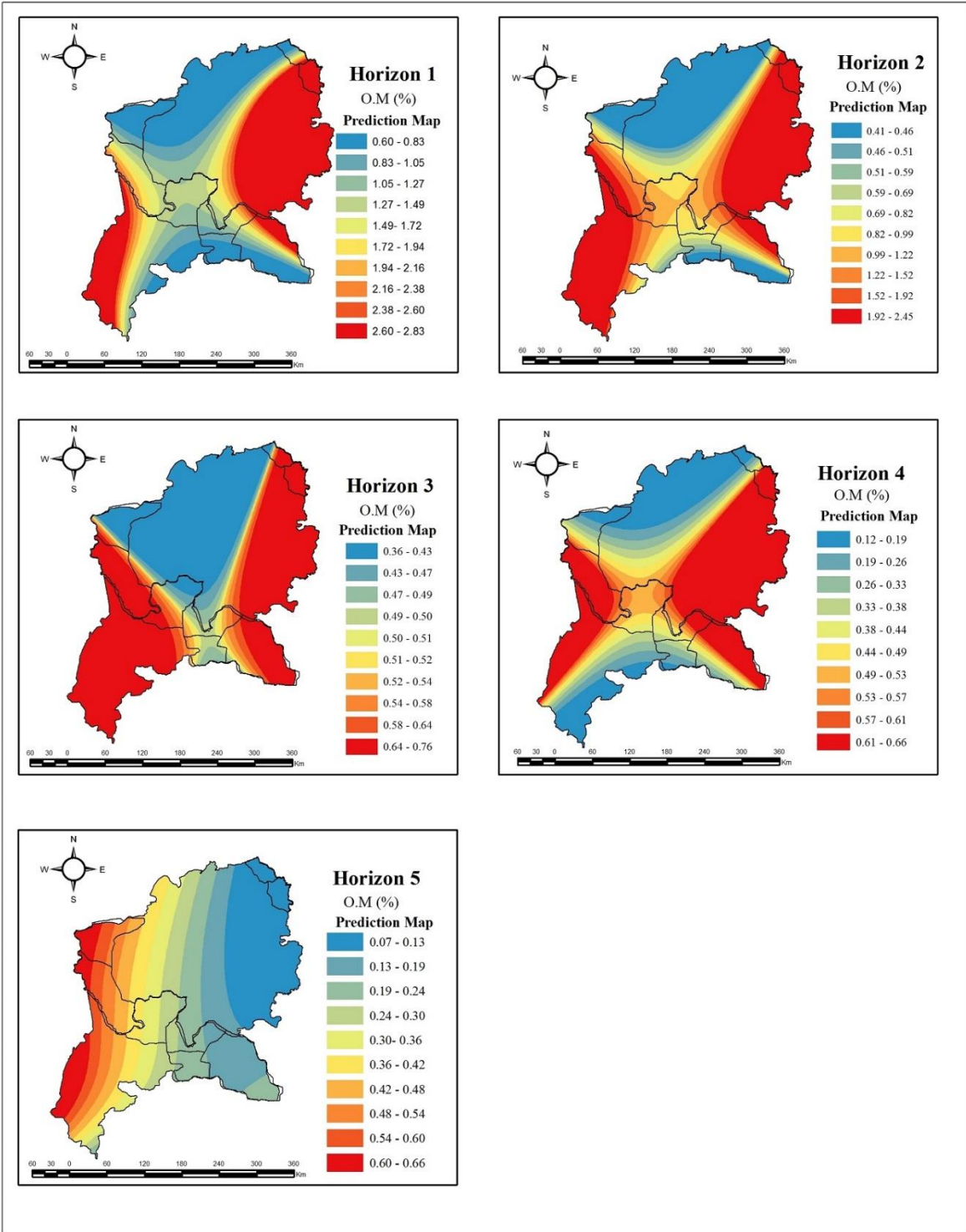


Figure 11. Spatial distribution of soil OM used for soil suitability assessment

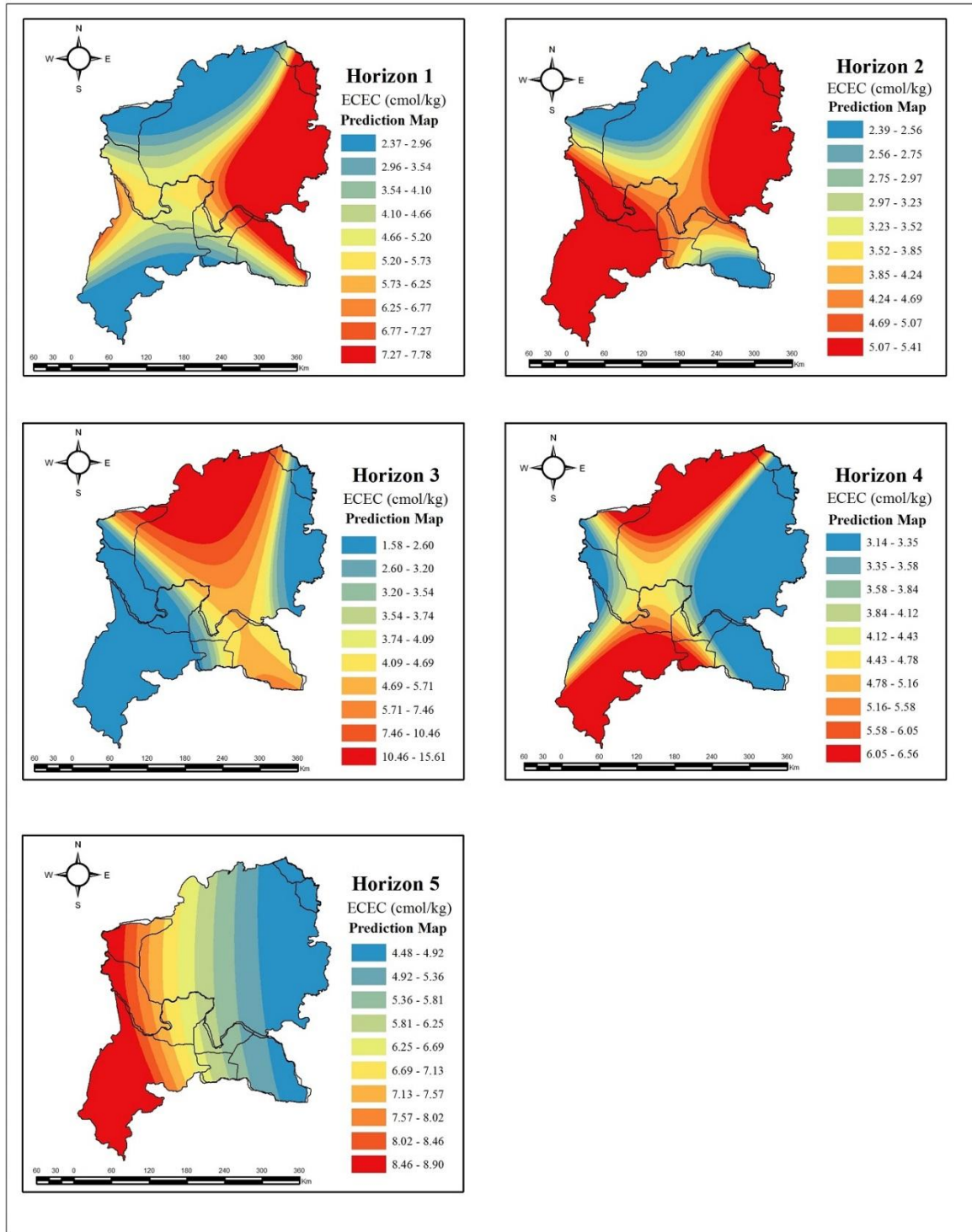


Figure 12. Spatial distribution of soil ECEC used for soil suitability assessment

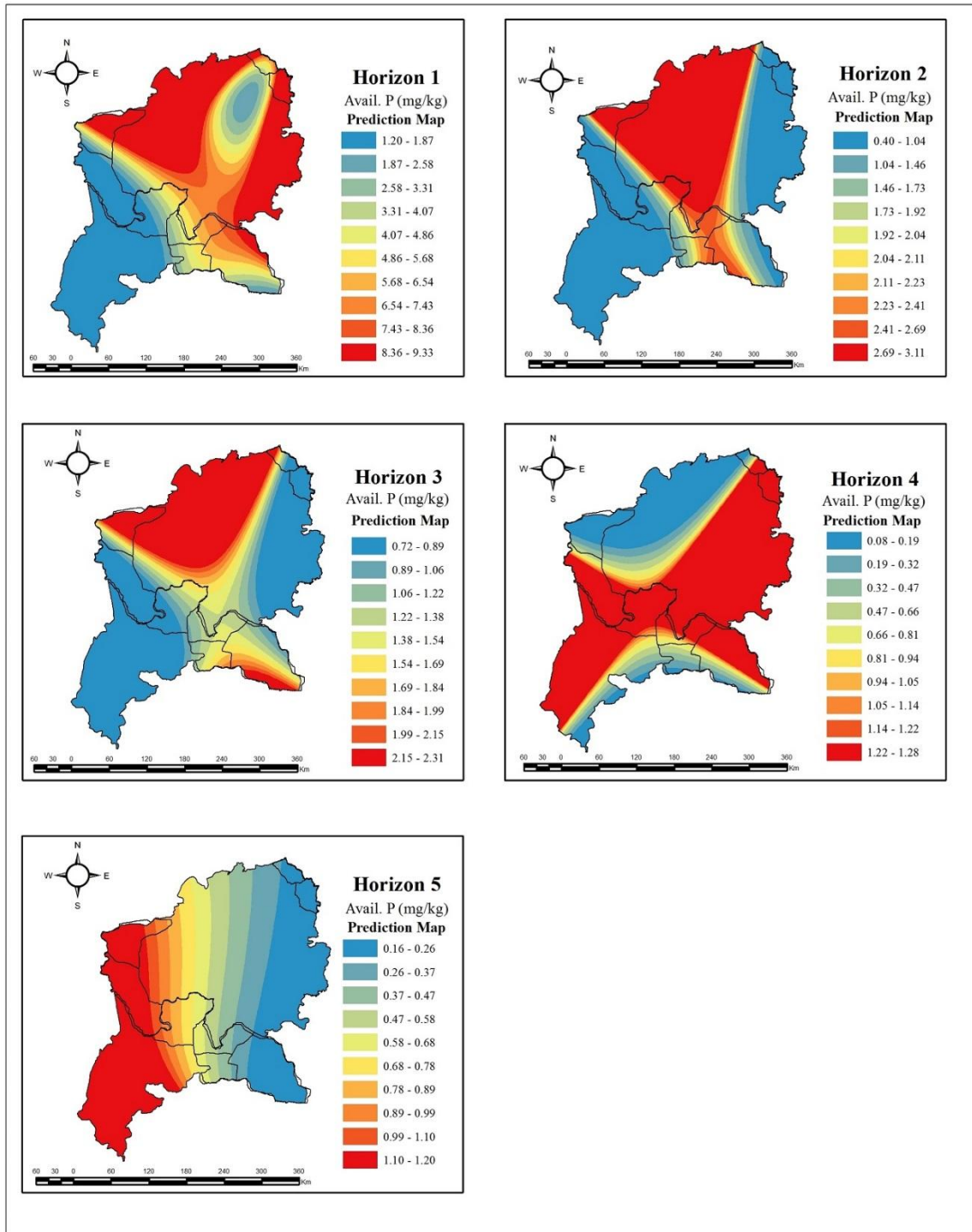


Figure 13. Spatial distribution of soil Available P used for soil suitability assessment

Appendix 2

Table 1. General information of site for Varempere series

Location	Nahari
Coordinates	09° 31' 42.3" N 002° 29' 28" W
Date of Description	December 5, 2013
Elevation	283.9 m
Parent Material	Granite
Physiographic Unit	Upper / Middle slope
Topography	Generally Undulating to Flat
Vegetation	Savanna
Slope Aspect	3 – 4%
Land Use	(Agricultural) Fallow
Past	Maize
Arable	90%
Surface cracks	Nil
Surface stones	About 10%
Surface rocks	Petro Plinthite
Erosion: Type	Sheet
Erosion: Degree	Moderate
Area Affected	All over the observed area
Moisture: Surface	Dry
Moisture: In Soil	Moist to Dry
Depth to Water Table	Not encountered

Table 2. Profile description of Varempere series

Horizon	Depth (cm)	Description
Ap	0-23	Brown (10YR5/3) dry; sandy loam; weak fine granular; friable; non sticky non plastic, many very fine, few fine and few medium roots, clear and smooth boundary.
Btcs1	23-28	Yellowish brown (10YR 5/8) dry; sandy clay; weak fine sub angular blocky; slightly sticky slightly plastic; few fine and medium MnO ₂ and Fe concretions; very few fine, very few medium roots; clear and smooth boundary.
Btcs2	38-52	Yellowish brown (10YR5/8) moist; sandy clay; weak to moderately medium sub angular blocky; slightly sticky slightly plastic; common medium MnO ₂ and Fe nodules; very few medium roots; diffused and smooth boundary;
Btv	52-102	Strong brown (7.5YR5/8) moist; sandy clay; massive; slightly sticky slightly plastic; many medium MnO ₂ and Fe concretions.

Table 3. General information of site for Kupela series

Location	Gbogdaa
Coordinates	09° 8' 16.2" N 002° 29' 15" W
Date	December 4, 2013
Elevation	216.3 m
Parent Material	Alluvium from Granite
Physiographic Unit	Lower Slope
Topography	Generally flat
Vegetation	Savanna
Slope Aspect	1 – 2%
Land Use	Fallow
Past	Rice
Arable	85%
Surface cracks	Nil
Surface stones	2%
Surface rocks	Nil
Erosion: Type	Sheet
Erosion: Degree	Slightly
Area Affected	All over the observed area
Moisture: Surface	Moist
Moisture: In Soil	Moist to Wet
Depth to Water Table	121 cm

Table 4. Profile description of Kupela series

Horizon	Depth (cm)	Description
Ap	0-21	Very dark grayish brown (10 YR 3/2) moist; sandy loam; weak fine crumbs; friable; non sticky non plastic; many very fine, many fine, few medium and very few coarse roots; diffuse and smooth boundary.
Acg	21-43	Very dark grayish brown (10 YR 3/2) moist; mottles dark yellowish brown (10 YR4/6); silty loam; weak fine sub angular blocky; friable; slightly sticky non plastic; many very fine, many fine, few medium and very few coarse roots; clear and smooth boundary.
Cg	43-80	Dark grayish brown (10 YR 4/2) moist; mottled dark yellowish brown (10 YR 4/6) sandy clay, massive; firm, sticky, plastic; very few very fine, few fine roots; clear and smooth.
Cgcs	80-105	Grayish brown (10 YR 5/2) moist; mottled dark yellowish brown 10 YR (4/6); Clay loam; massive, firm, slightly plastic; few common fine and medium quartz stones and gravels, few MnO ₂ and Fe concretions; diffuse and smooth boundary.
Cgcs2	105-122	Grayish brown (10 YR 5/2) moist; mottled yellowish brown (10 YR 5/2); Clay; massive; firm; sticky; plastic; few common and medium quartz stones and gravels; few MnO ₂ and Fe concretion.

Table 5. General information of site for Kpelesawgu series

Location	Famisa
Coordinates	10° 11' 55.4" N 000° 15' 50.2" W
Date	December 13, 2013
Elevation	140.1 m
Parent Material	Voltaian Shale
Physiographic Unit	Middle slope
Topography	Generally Undulating to Flat
Vegetation	Interior Savanna (grass, short shrubs with scatted Sheanut tress)
Slope Aspect	3 - 4 %
Land Use	Agricultural (Rainfed Arable Cultivation and Shifting Cultivation)
Past	Maize
% Arable	65
Surface cracks	Nil
Surface stones	About 10%
Surface rocks	Few Petro Plinthite
Erosion: type	Sheet
Erosion: degree	Moderate
Area affected	All over the observed area
Moisture: surface	Dry
Moisture: in Soil	Moist to Dry
Depth to water table	Not encountered

Table 6. Profile description of Kpelesawgu series

Horizon	Depth (cm)	Description
Ap	0-13/24	Yellowish brown (10YR5/4) dry; sandy clay; weak fine granular; non sticky non plastic; many very fine, many fine, few medium and very few coarse roots; common very fine and common fine pores; clear and wavy boundary.
Btcs	13/24-74	Brown (7.5YR5/4) dry; sandy clay; weak to moderate fine and medium sub angular blocky; slightly hard; firm; slightly sticky, slightly plastic; common manganese dioxide and iron nodules; common very fine, few fine and very few medium roots; common very and common fine pores; very few fine artefacts; clear and smooth boundary.
BCtgcs	74-115	Olive yellow (2.5 Y 6/6) dry; mottled strong brown (7.5 YR 5/8); sandy clay; massive; very hard; firm; slightly sticky, slightly plastic; common fine and medium MnO ₂ and Fe nodules; very few medium roots.

Table 7. General information of site for Lima series

Location	Alhassan Kura
Coordinates	08° 41' 39.6" N 001° 28' 29.7" W
Date	November 19, 2013
Elevation	103 m
Parent Material	Alluvial materials from Clay Shales and Mudstones
Physiographic Unit	Lower Slope
Topography	Generally Flat
Vegetation	Grass interspersed with woody vegetation and sheanut tress
Slope Aspect	2 - 3 %
Land Use	Agricultural (Shifting Cultivation)
Past	Fallow
Arable	85%
Surface cracks	Nil
Surface stones	Nil
Surface rocks	Nil
Erosion: type	Sheet
Erosion: degree	Slightly
Area affected	All over the observed area
Moisture: surface	Dry
Moisture: in Soil	Dry
Depth to Water Table	Not encountered

Table 8. Profile description of Lima series

Horizon	Depth (cm)	Description
Ap	0 – 11	Grayish brown (10YR5/2) dry; sandy loam; weak fine granular; slightly hard, friable, non-sticky non-plastic; many very fine, few fine, very few medium roots; common fine pores; clear and smooth boundary.
Bg	11 – 20	Light brownish gray (10YR6/2) dry; mottled strong brown (7.5YR 5/6); silty loam; weak fine sub-angular blocky; slightly hard, friable, slightly sticky non-plastic; very few very fine, few fine, many medium, few coarse roots; common very fine pores; clear and smooth boundary.
Btg1	20 – 38	Pinkish Gray (7.5YR7/2) dry; mottled (7.5 YR 6/8) silty clay; weak medium sub-angular blocky; slightly hard, friable, slightly sticky slightly plastic; few very fine, few fine and many coarse roots, few fine pores; few continuous irregular clay coatings; gradual and smooth boundary.
Btg2	38 – 63	Pinkish Gray (7.5YR7/2) dry; mottled (7.5YR6/8); silty clay; moderately medium sub-angular blocky; slightly hard; friable, slightly sticky slightly plastic; very few very fine and many coarse roots; few very fine pores; clear and smooth boundary.
Btgkcs1	63 – 95	Light Gray (10YR7/2) dry; mottled Strong brown (7.5YR5/8); silty clay; moderately medium angular and sub-angular blocky;

slightly calcareous; few fine rounded black manganese and Calcium carbonate concretions; hard, firm, slightly sticky slightly plastic; very few fine roots; few fine pores; clear and smooth boundary.

Btgkcs2	95 - 125	Light brownish gray (10YR6/2) dry; Mottled Strong Brown (7.5YR 5/8); silty clay, massive; slightly calcareous; few fine rounded black Mn and CaCO ₃ concretions; very hard; firm, sticky plastic; common MnO ₂ ; very few fine pores.
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Table 9. General information of site for Ejura series

Location	Lilai
Coordinates	07° 36' 10.3" N 001° 005' 44.2" W
Date	28/11/13
Elevation	173.7 m
Parent Material	Fine Grained Feldspathic -Voltaian Sandstone
Physiographic Unit	Upper Slope
Topography	Generally Undulating
Vegetation	Forest Transitional
Slope Aspect	3 - 5 %
Land Use	Fallow
Past	Fallow
Arable	95%
Surface cracks	Nil
Surface stones	Nil
Surface rocks	Nil
Erosion: Type	Sheet
Erosion: Degree	Slightly
Area Affected	All over the observed area
Moisture: Surface	Moist
Moisture: In Soil	Moist
Depth to Water Table	Not encountered

Table 10. Profile description of Ejura series

HORIZON	DEPTH (cm)	DESCRIPTION
Ap	0 – 32	Dark reddish brown (5YR3/3) moist; sandy loam; weak fine granular; friable, non-sticky non plastic; many very fine, many fine, many medium, very few coarse roots; common very fine and many fine pores; common earthworm channels and other insect activity ; clear and smooth boundary.
BAt	32 – 51	Reddish brown (5YR4/4) moist; sandy clay loam, weak fine sub-angular blocky; friable non slightly sticky non plastic; very few fine, many medium, very fine coarse root; common very fine and common fine pores; common earthworm and other insect channels; clear and smooth boundary.
Bt1	51 – 85	Yellowish Red (5YR4/6) moist; sandy clay; weak to moderately medium sub-angular blocky; firm, slightly sticky slightly plastic; many very fine, many fine, very few coarse roots; many very fine and many fine pore; few earthworm channels and other insect activity; clear and smooth boundary.
Bt2	85 – 113	Reddish Brown (5YR5/3) moist; sandy clay; moderately medium sub-angular blocky; firm, slightly sticky non plastic; few fine, few medium and very few coarse roots; few to common fine pore; clear and smooth boundary.

Btcs	113 – 140	Red (2.5YR5/8) moist; sandy clay; moderate medium sub-angular blocky firm, slightly sticky non plastic; few fine and medium manganese dioxide and iron nodules; very few very fine coarse roots; very few very fine and fine pores.
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Table 11. General information of site for Damongo series

Location	Shafa Zongo
Coordinates	07° 44' 4.6" N 000° 43' 0.1" W
Date	28/11/13
Elevation	171.9 m
Parent Material	Coarse Voltaian Sandstone
Physiographic Unit	Upper Slope
Topography	Generally Undulating
Vegetation	Forest Transitional
Slope Aspect	3 - 4 %
Land Use	Agriculture (Cropping)
Past	Maize
% Arable	90% of area
Surface cracks	Nil
Surface stones	Nil
Surface rocks	Nil
Erosion: Type	Sheet
Erosion: Degree	Slightly
Area Affected	All over the observed area
Moisture: Surface	Moist
Moisture: In Soil	Moist
Depth to Water Table	Not encountered

Table 12. Profile description of Damongo series

HORIZON	DEPTH (cm)	DESCRIPTION
Ap	0-22	Brown (7.5 YR 4/2) moist; Sandy clay; very weak fine granular; friable; non sticky non plastic; common very fine, many fine, few medium, very few coarse roots; few very fine and fine interstitial pores; few borrows and earthworm channels; clear and smooth boundary.
BA	22- 36	Reddish brown (5YR 5/4) moist; sandy loam; very weak fine granular; friable; non sticky non plastic; many very fine; many fine, few medium, very few coarse roots; ; few very fine and fine interstitial pores; few borrows, Charcoal and earthworm channels; clear and smooth boundary.
Bt1	36-71	Yellowish red (5YR 5/8) moist; Sandy clay; weak fine and medium sub angular blocky; friable; slightly sticky slightly plastic; very few very fine, few medium, very few coarse roots; very few, very fine and fine interstitial pores; few borrows; clear and smooth boundary.
Bt1	71-101	Dark red (2.5 YR 4/6) moist; Sandy clay; weak fine and medium sub angular; friable; slightly sticky slightly plastic; very few very fine, few medium, very few coarse roots; very few, very fine and fine interstitial pores; diffuse and smooth boundary

Bt3	101-135	Dark red (2.5 YR 4/8) moist; Sandy clay; weak medium fine sub angular; friable; slightly sticky slightly plastic; very few coarse roots; very fine interstitial pores; clear and smooth boundary.
Btcs	135-159	Red (10R 4/8) moist; Clay loam; moderately medium sub angular; firm, slightly sticky slightly plastic; few fine and medium manganese dioxide and Iron concretions.

Table 13. General information of site for Mimi series

Location	Naniik
Coordinates	10° 34' 51.6" N 000° 4' 48.1" E
Date	13/12/13
Elevation	376.1 m
Parent Material	Feldspartic Voltaian Sandstone
Physiographic Unit	Upper slope
Topography	Generally Undulating
Vegetation	Guinea Savanna (Tall and short grasses with short Shrubs)
Slope Aspect	2 - 3 %
Land Use	Agricultural (Fallow- Shifting Cultivation)
Past	Maize
% Arable	90
Surface cracks	Nil
Surface stones	Nil
Surface rocks	Nil
Erosion: Type	Sheet
Erosion: Degree	Slightly
Area Affected	All over the observed area
Moisture: Surface	Dry
Moisture: In Soil	Moist
Depth to Water Table	Not encountered

Table 14. Profile description of Mimi series

HORIZON	DEPTH (cm)	DESCRIPTION
Ap	0-22	Brown (7.5 YR 5/4) moist; loamy sand; very weak very fine granular; non sticky non plastic; many very fine, many fine and very fine medium roots; common very fine and fine pores; gradual and smooth boundary
AB	22-40	Strong brown (7.5 YR 5/6) moist; sandy loam; weak fine and medium granular; non sticky non plastic; common very fine; very few medium and very few coarse roots; common very fine and few fine pores; clear and smooth boundary.
Btcs1	40-58	Yellowish red (5 YR 5/8) moist; sandy clay; weak fine and medium sub angular blocky; friable; slightly sticky slightly plastic; few fine Manganese dioxide and iron concretions; common very fine and few fine pores; diffused and smooth boundary.
Btcs2	58-114	Dark red 2.5 YR (4/8) moist; clay loam; moderately weak fine and medium sub angular blocky; firm; slightly sticky slightly plastic; very few fine and medium MnO ₂ and Fe; common very fine and few fine and few medium pores; diffuse and smooth boundary.
Bt	114-165	Dark red 2.5 YR (4/8) moist; clay loam; moderately medium sub angular; firm; slightly sticky slightly plastic;

very few coarse roots; common very fine and few fine and
few medium pores.

Table 15. General information of site for Wenchi series

Location	Kwayasi
Coordinates	08° 14' 1.2" N 000° 42' 25" W
Date	29/11/13
Elevation	159.1 m
Parent Material	Clay Shales
Physiographic Unit	Upper to Middle slope
Topography	Generally Undulating
Vegetation	Savanna (Tall, Medium and short grassland with scatted Trees)
Slope Aspect	2 - 3 %
Land Use	Agricultural (Shifting Cultivation)
Past	Fallow
% Arable	Nil
Surface cracks	Nil
Surface stones	20 - 30%
Surface rocks	Petro Plinthite
Erosion: Type	Sheet
Erosion: Degree	Moderate
Area Affected	All over the observed area
Moisture: Surface	Dry
Moisture: In Soil	Dry
Depth to Water Table	not encountered

Table 16. Profile description of Wenchi series

HORIZON	DEPTH (cm)	DESCRIPTION
Ap	0 - 14	Brown (10 YR 5/3) dry, sandy loam; weak fine granular; loose, non-sticky non plastic; common medium and coarse Manganise dioxide and iron nodules; many very fine, many Fine, many medium and very few coarse roots; few borrows and earthworm channels; clear and smooth boundary.
Btcs	14 - 29	Pale Brown (10 YR 6/3) dry; sandy clay; weak fine to medium sub-angular blocky; Soft; coarse Manganese dioxide and iron concretions; very few fine, few medium, very few very fine coarse roots; abrupt and smooth boundary.

Table 17. Rated landscape and soil quality indicators according to FAO (1976).

Soil Series	Topog slope (%)	Drainage	Soil Texture		Structure		Coarse Frag		Effective Soil Depth	Rating		Limitation
			Top	Sub	Top	Sub	Top	Sub		Class	Subclass	
Varempere	S1	S1	S2	S2	Sq1	Sq3	S2	S3	S1	S3	s, c	S3cs
Kupela	S1	S3	S2	S2	Sq1	Sq4	S1	S3	S1	S3	s, c, w	S3csw
Kpelesawgu	S1	S2	S1	S1	Sq1	Sq4	S1	S3	S1	S3	c, s	S3cs
Lima	S1	S3	S2	S2	Sq1	Sq3	S1	S2	S1	S3	w, s	S3ws
Ejura	S1	S1	S2	S2	Sq1	Sq2	S1	S1	S1	S2	x	S2x
Damongo	S1	S1	S2	S2	Sq1	Sq2	S1	S1	S1	S2	x	S2x
Mimi	S1	S1	S2	S2	Sq1	Sq2	S1	S1	S1	S2	x	S2x
Wenchi	S1	S1	S1	S1	Sq1	Sq1	N1	N1	S3	N1	c	N1c

Where c = coarse fragments, t = topography, w = drainage, s = structure, x = texture, sq is from the Peerlkamps soil structure assessment scale (Boekel and Peerlkamp, 1956)

Table 18. DEFINITE Problem Definition Effects Table for each Soil Series Criteria.

Effects	Alternative Soil Series for Soil Suitability Management							
	Northern Region				Brong Ahafo			
	Kpelesawgu	Varempere	Kupela	Mimi	Ejura	Damongo	Wenchi	Lima
Revenue (Yield x price)	720	744	720	1360	3120	1980	600	1440
Fertilizer cost (amount x price) GHC ha ⁻¹	-363.76	-363.76	-363.76	-363.76	-363.76	-363.76	-363.76	-363.76
SQI-score (Adiku)	33.83621	36.40437	36.71368	44.60836	42.11185	47.63424	49.39177	36.6166
Labour cost (GHc ha ⁻¹)	-677.75	-677.75	-677.75	-677.75	-717.75	-717.75	-717.75	-717.75
Soil erodibility (MCR)	-0.71	-0.26	-0.33	-0.15	-0.75	-0.39	-0.98	-0.55
Conservation practice	-10	10	-10	30	10	10	30	20
Fournier Index	174.79	141.86	141.86	174.79	178.94	178.94	178.94	144.8
Distance to Market (Rating (1/d ²))	0.003	0.0004	0.0044	0.003	0.0016	0.04	0.01	0.0016

Negative values indicate cost; positive values are benefits

Table 19. Recorded coordinates of assessed soil profiles.

Soil Series	LATITUDE				LONGITUDE			
	D	M	S		D	M	S	
Wenchi	8	14	1.2	N	0	42	25	W
Varempere	9	31	42.3	N	2	29	28	W
Mimi	10	34	51.6	N	0	4	48.1	E
Lima	8	41	39.6	N	1	28	29.7	W
Kupela	9	8	16.2	N	2	29	15	W
Kpelesawgu	10	11	55.4	N	0	15	50.2	W
Ejura	7	36	10.3	N	1	5	44.2	W
Damongo	7	44	4.6	N	0	43	0.1	W