EFFECTS OF SOIL AMENDMENTS ON PHYSICAL PROPERTIES AND MAIZE GRAIN YIELD IN POORLY RESPONSIVE SOILS OF WESTERN KENYA

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DECLARATION

DECLARATION BY THE CANDIDATE

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To my family, husband, Richard and son, Edward for their support, sacrifices and love.

To my parents and siblings for their encouragement and motivation.

ABSTRACT

Poor soil responsiveness to fertilizer application is an emerging problem whose cause is yet to be well understood. This was the basis for a study in Western Kenya to unravel the underlying physical characteristics of these soils that influence the performance of fertilizer use on maize grain yield. The study was conducted on eight on-farm fields equally distributed in Busia-North and Bungoma-Southwest counties during the long rain (LR) and short rain (SR) seasons of 2015. A RCBD was adapted with three fertilizer treatments as amendment strategies: an absolute control, a combination of organic and inorganic fertilizers and a pure inorganic fertilizer. The latter two fertilizer treatments aimed at providing balanced nutrition consisting of primary macro (N, P and K), secondary macro- (Ca) and micro- (Zn and Cu) nutrients. The influence of the amendments on water infiltration, penetration resistance (at three depths; 10, 20 and 30 cm) and maize grain yield was assessed twice during the study period. A study on inherent physical characteristics (texture, stable aggregates and water content) at the onset revealed a restriction for crop roots in the soil subsurface layers. In each region, two of the four fields had adequate rooting depth (> 20 cm) while the two had inadequate (< 20 cm) for maize growth. Texture across all the fields was predominantly sand of classes: sandy loam, loamy sand and sandy. Stable aggregates relied on silt due to low C and clay contents. Infiltration rates of the shallow fields (9.25 cm hr^{-1}) were lower than that of the deep fields (12.98 cm hr^{-1}); while addition of organic amendments increased water movement significantly. Penetration resistance increased with depth. Upper soil layer had < 0.5 MPa readings while at 30 cm depth, > 3 MPa as the critical threshold limiting rooting of crops. Compaction was prominent in shallow fields compared to those with adequate rooting depth. The overall yield was low (< 1 t ha^{-1}) where amendments were not applied and significantly increased with nutrients application (> 3 t ha^{-1}). Higher grain yield was observed in LR (3.46 t ha^{-1}) compared to SR (2.13 t ha^{-1}). Combination of organic and inorganic fertilizers improved water infiltration and reduced compaction as organic matter aids in overall soil permeability. However, shallow fields faced further physical constraint where addition of organic materials was insignificant. Designation of proper nutrient amendments and practices such as deep tillage is required to alleviate challenges in PRS.

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LIST OF ABBREVIATIONS

BD – Bulk density

CEC – Cation Exchange Capacity

Cm hr^{-1}- Centimetre per hour

DAP – Di-Ammonium Phosphate

FC – Field capacity

F.T. – Fertilizer treatment

FYM – Farm Yard Manure

g cm^{-3} – grams per cubic centimeters

Ha – hectares

INRM - Integrated Natural Resource Management

Kg ha^{-1} – kilograms per hectare

MOA – Ministry of Agriculture

MOP – Muriate of Potash

MPa – Megapascals

PAW – Plant available water

POC – Particulate Organic Carbon

PR – Penetration resistance

PRS – Poorly Responsive soils

PWP – Permanent Wilting point

SOC – Soil Organic Carbon

SOM – Soil Organic Matter

SWC - Soil Water characteristic Curve

T ha^{-1} – tonnes per hectare

TSP – Triple superphosphate

VCR – Value Cost Ratio

VLIR - ‘Vlaamse interuniversitaire raad (Flemish interuniversity council)

θm – Mass water content

θv – Volumetric water content

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May God bless you.

CHAPTER ONE

INTRODUCTION

1.1 Soil Infertility prominence in SSA

Sub-Saharan Africa (SSA) countries (including Kenya) experience food insecurity and consequently poverty (Fairhurst, 2012). Approximately, 70% of the population rely on farming with 65% providing their income (Garrity, Akinnifesi, Ajayi, Sileshi, Mowo, Kalinganire *et al.*, 2010). However, the region faces food production decline per capita at an average of 20 – 30 % (Keating, Carberry, & Dixon, 2013). Low agricultural production in this region is associated to the lack of adoption of new technology. Maize grain yields less than 1 t ha^{-1}; yet the area could produce about 6 t ha^{-1} (MOA, 2014; Jaetzold, Schimdt, Hornetz, & Shisanya, 2005).

Mainly, continuous cultivation without replenishment of nutrients and low application of methods that can improve soil fertility status, has led to degradation and consistent low maize grain yields (MOA, 2014; FAO, IFAD & WFP, 2012). In addition, agricultural practices in this area are mainly rainfed and thus affected by changes in climate. The extent to which agroecosystems are degraded creates uncertainty of obtaining higher crop yields (Jones & Thornton, 2003). These farmers are challenged by planning and adopting appropriate land use methods (Fairhurst, 2012). In addition, soil properties, particularly the physical and their role in crop production are necessary, yet they are understudied in the tropics (Dunjana, Nyamugafata, Nyamangara, & Mango, 2014).

Food insecurity is estimated to grow by 30% in this region (Funk & Brown, 2009). This creates a need for studying soils comprehensively and understanding their constraints.

1.1.1 Key constraints to food production

The international policy community considers that proper utilization of tropical soils will tackle issues related to food security and land degradation (Sanchez, Palm, & Buol, 2003). Agricultural land increases by more than 10% annually in SSA (Fairhurst, 2012). This owes to the anticipated population growth creating intensification of agricultural production (Vanlauwe, Blomme, & van Asten, 2013), however, the maize grain yield has not increased. Also, the increase in population has further reduced agricultural land size where 80% of agricultural land is less than 2 hectares (ha) (Garrity *et al.*, 2010). This has resulted to smallholder farmers, dominating overall agricultural growth such a in Western Kenya. Maize is a staple of this region but produces less than 1 t ha^{-1} while expected production is 6 t ha^{-1} (MOA, 2014).

Little usage of fertilizer has caused nutrient removal from soil, lessening of nutrients reserves and soil organic matter (SOM); with time, this has damaged the structures within agroecosystems to take up water and nutrients (Vanlauwe *et al.*, 2011; Sanginga & Woomer, 2009). Farmers are unable to access fertilizers due to their high prices. Low precipitation as a result of drought worsens this situation due to low farm outputs. Small holder farmers are reported to be able to about 8 to 10 kg ha^{-1} (African Fertilizer Summit, 2006). Constraints felt on food production in this region include climate changes, low adoption of technology, pest and diseases.

In addition, the soils in the region have a low capacity to retain nutrients and moisture which leads to losses of nutrients (Bagula, Pypers, Mushagalusa, & Muhigwa, 2014). The result of all this is little grain yield and land degradation.

1.1.2 Occurrence of poorly responsive soils

In an attempt to amend degraded soils, Vanlauwe, Batiano, Chianu, Giller, Merckx, Mokwunye *et al.*, (2010) distinguished; *responsive soils* whose yield increases after application of fertilizer and *poorly responsive soils* whose yield improves stagnates on application of similar inputs. Poorly responsive soils (PRS) are defined as those which have no significant increase in yield after addition of nitrogen (N), phosphorus (P) and potassium (K) fertilizers with a Value Cost Ratio (VCR) of less than two (Njoroge, Otinga, Okalebo, Pepela, & Merckx, 2018; Njoroge, Otinga, Okalebo, Pepela, & Merkx, 2017). Lack of significant increase in yield after fertilizer application raises concerns. This occurs in scenarios where nutrients and carbon stocks have been depleted (Fairhurst, 2012). Also, erosion of soil is imminent which leads to the loss of beneficial nutrients and organic matter as well as limiting root penetration.

In Western Kenya, research done is on chemical imbalances in soils which gives nutrients amounts to be applied with an aim at increasing yield by mainly reducing soil acidity (Keino, 2015; MOA, 2014; Omenyo, 2013; Otinga, 2012). However, soils of this region have heterogeneity due to degraded systems (Vanlauwe *et al.*, 2010; Titonell, Vanlauwe, Leffelaar, Shepherd, & Gilller, 2005) with some areas being poorly responsive.

Njoroge *et al.,* (2017) reported on the occurrence of PRS in 48% of studied fields in Western Kenya which was associated with nutritional imbalances; particularly the micronutrients. However, PRS remain scarcely documented and their causes are still not well understood.

1.1.3 Nutrient imbalances and low C stocks as precursors of PRS

A research carried out in Western Kenya unveiled how the gradient of soil fertility decreases while moving away from household (Titonell *et al.,* 2005). This owes to use of waste materials and manure being applied on land near the houses while those located further do not receive similar applications. Negative nutrient balances are created at farm creating heterogeinity (Titonell *et al.,* 2005). The balance of nutrients in agricultural lands in SSA is reported as the most negative in the world. Fertilizer rate is estimated at 8 to 10 kg ha^{-1} compared with 110 kg ha^{-1} application for the world (African Fertilizer Summit, 2006). In addition, extremely steep relief in these regions makes the soils to be highly susceptible to soil erosion by water (Bagula *et al.,* 2014). Therefore, the recommended nutrition regime does not meet their needs.

Previous research shows that in order to increase yield, there is need to apply inputs; both organic and inorganic. The use of appropriate and recommended quantities of inputs is results to positive nutrient balances on smallholder farms (Zingore, Murwira, Delve, & Giller, 2007). In order to curb some of these challenges, there is need to ensure sufficient carbon (C) stocks in the soil. Sufficient carbon ensures that the quality of soil well-balanced and thus yield increases (Vanlauwe *et al.,* 2010).

The stable fraction of organic matter in soils aids in supplying nutrients to crops, buffering soil pH, water holding capacity and assists in structural. Soil organic matter has a multifaced nature which gives it the ability to serve different functions. Additionally, its various fractions can pinpoint to efficiencies which are related to the soil physical attributes (Sanchez *et al.*, 2003). Maize grain yield in this region can be increased by using available organic resources to add to the little inorganic fertilizers that can be purchased (Vanlauwe *et al.,* 2010; Sanchez, 2010; Garrity *et al.,* 2010).

1.1.4 Soil physical parameters and land use effect on poorly responsive soils

However, smallholder farms in Western Kenya are faced by an enormous issue. Continual land cultivation has resulted in soil infertility and erosion. In addition, the farms rely on little rainfall which has resulted in unsustainability. Physical deterioration of these farms emanates from characteristics such as low ability of water to infiltrate, surface run-off, erosion, compaction and low porosity (Dexter, 2004).

Soil physical properties are crucial for they as link chemical and biological attributes hence soil quality relies on their characteristics (Dexter, 2004); these properties are thus important in understanding of land degradation and designing proper approaches of land use. Poor soil physical qualities result from degradation brought about by land mismanagement. Excessive tillage and lack of cover crops or leaving their residues leads to erosion and compaction especially in areas such as tropics where rainfall intensity is high. The loss of topsoil is associated with changes in rooting depth and washing away of organic matter (Elsheikh, Ouerghi, & Elhag, 2015).

Compaction impairs the soils' ability to retain water because it reduces infiltration rate and porosity leading to poor structural formation and high bulk density (Hamza & Anderson, 2005; Nawaz, Bourrié, & Trolard, 2013).

This study was focused on assessing soil physical parameters which are inked to poor responsiveness to fertilizer inputs and if addition of organic materials while adequately providing nutrition could result in their amendment. This research was superimposed in 2015 on an on-going project by 'Vlaamse Interuniversitaire Raad' (VLIR; Flemish Interuniversity Council) aimed at identifying nutritional imbalances in PRS and rehabilitating by balanced fertilizer strategy. The VLIR research project began in 2014 where 60 poorly responsive farms were identified and NPK fertilizer trials conducted in both long and short rain seasons. Out of the 60 farms, 18 of them did not have significant yield after NPK application. These 18 farms thus formed the basis of this particular study. The presumed causes of poor soil response were high sand content (of more than 50%) and large slope gradient (greater than 5%); in addition, deficient nutrients which influenced the crop roots, moisture retention and nutrients availability thus affecting overall grain yield.

1.2 Problem statement

Poor soil responsiveness to application of straight fertilizers is a persistent problem experienced by smallholder farmers in Western Kenya. Persistent low yield (< 1 t ha^{-1}) or lack of yield increase after application of N, P, K nutrients has become common trend in the Western Kenya (Nziguheba *et al.,* 2010).

Njoroge *et al.,* (2017) and Vanlauwe *et al.,* (2010) reported that application of fertilizers gives low or insignificant yield increase which is of little economic benefit to the farmers, at a value cost ratio (VCR) of less than two. Research conducted on crop production constraints mainly focus on topsoil attributes, nutrient management and chemical change in the soil, however, little attention is paid on the effect of soil physical properties on the efficiency of the applied nutrients. Soil physical degradation is thought to be one of the drivers of poor responsiveness to fertilizer application (Fairhurst, 2012).

Soil physical properties such as abrupt soil texture changes, shallow depth, poor infiltration, restricted root penetration, decline in soil structure, loss of topsoil and compaction are among the physical attributes that negatively affect crop root system by creating poor response to inputs and consequently low crop production (Hartmann, *et al.*, 2008; Elkateb, Chalaturnyk, & Robertson, 2003). Defective management of land systems by farmers, particularly results in surface runoff and erosion leading to loss of topsoil and nutrients (Craswell & Lefroy, 2001). These effects are mostly felt by the people living in rural areas (Muchena, 2008) who mainly depend on agriculture.

In order to understand physical constraints of soils, the structural stability is of key importance. This parameter is linked to aggregate stability; making it the main indicator of physical soil health (Murphy, 2014). Soils made up of upper sandy textured horizons like those found in Western Kenya have more diverse physical constraints which makes them more sensitive to crusting and compaction due to low aggregation. The mineralogy of soils in this area is mainly made up of kaolinite, quartz and sesquioxides.

In order to increase yield in these soils, they require addition of nutrients from fertilizers as well as building up the C stocks by adding organic materials. Six, Paustin, Elliott, & Combrink (2000) reported that when soils lack sufficient SOM, aggregates tend to be formed from sesquioxides. Cebula (2013) noted similar observation formation of aggregates in tropics relies on clay mineral amount and not soil organic carbon (SOC), due to no or low application of organic amendments in the farms. In Western Kenya, where maize is a staple food, continuous cropping and carbon loses contributes to the changing distribution and stability of soil aggregates.

1.3 Justification

Improving productivity in these PRS is a major challenge that requires large investments over multiple cropping seasons before any meaningful yield responses can be obtained; requiring several strategies. These strategies include; - use of organic resources to restore SOM; combination of various nutrients that are deficient in these soils to increase biomass production and retain crop residues; and use of moisture conservation techniques to increase water available for crops (Zingore & Johnston, 2013). Soil organic matter is thus essential for agricultural production due to its positive effects on the physical attributes (Cebula, 2013). In particular, additions of organic matter have been seen to improve the soil structure and in turn influence soil water movement and retention, crusting, nutrient recycling, root penetration and crop yield (Herencia, García-Galavís, & Maqueda, 2011).

By addition of organic matter and retention of crop residues after harvest, soil physical parameters can be remedied such as reduction in bulk density, improvement in aggregate stability, increase in water infiltration and porosity, and reduction in erodibility (Cebula, 2013; Herencia *et al.*, 2011; Bronick & Lal, 2004). Soil organic matter is considered the thread that links the physical, chemical and biological properties of soils. By its incorporation in poor responsive soils, the problem could be alleviated.

Infiltration is noted to increase by 27% in sandy loam soils with high SOM recording in the humid subtropical climate (Franzluebbers, 2002). The infiltration rate for sandy clay loam was noted to be 2 mm min^{-1} lower than on sandy clay (Cebula, 2013) resulting from the high bulk density. Recommendations were made to study the compaction of the sub-soil as a restricting factor to root growth and crop yield.

1.4 Objectives

1.4.1. Overall objective

To determine influence of soil amendments on physical properties and consequently, on the yield of maize grain in poorly responsive soils (PRS) of Western Kenya.

1.4.2 Specific Objectives

1. To assess the underlying physical characteristics of PRS and their relationships
2. To determine how soil amendments, rainfall amount and rooting depth affect water movement in PRS of Western Kenya
3. To assess how soil amendments, rainfall amount and rooting depth affect soil compaction in PRS of Western Kenya

4. To evaluate the effect of soil amendments, rainfall amount and rooting depth on the yield of maize in PRS of Western Kenya

1.5 Hypotheses

H_1: There are underlying physical attributes that can be used as indicators of poor responsiveness in Western Kenya

H_1: When rainfall amount is adequate, addition of soil amendments and adequate rooting depth increases water movement in PRS of Western Kenya

H_1: When rainfall amount is adequate, addition of soil amendments and adequate rooting depth decreases soil compaction in PRS of Western Kenya

H_1: When rainfall amount is adequate, addition of soil amendments and adequate rooting depth increases maize grain yield in PRS of Western Kenya

CHAPTER TWO

LITERATURE REVIEW

2.1. Land Degradation in the tropics

Land degradation can result from natural or human causes. Natural causes include those which are driven by climatic conditions that determine the capacity of land to generate biomass and ground cover, water quantities and biodiversity. Other natural causes include topography which influences slope and vulnerability to erosion by wind and water (Oldeman, 2000). Human-induced causes are mainly driven by land use management, economic and social factors. Some of the natural causes have humans playing a role such as deforestation, landslides, forest fires and drought. The drivers of these are deeply rooted in the economic and social factors such as population pressures, poverty, lack of markets and infrastructure, poor governance and illiteracy. These relationships are however not expressed statistically hence difficult to prove.

Land degradation in the tropics manifests itself in the form of soil erosion, gully formation, soil fertility loss, water scarcity and reduction in crop yield (Nkonya, Gerber, von Braun, & De Pinto, 2011). Land degradation refers to a long-term decline within a functional ecosystem brought about by disturbances from which the land itself cannot recover unaided (Bai, Dent, Olsson, & Schaepman, 2008). Biophysical factors such as slope gradient determines soil erosion risk due to climatic conditions like precipitation, temperature and wind as well as unsustainable land management practices including nutrient mining of soils and deforestation have been the main contributors to land degradation (Nkonya *et al.*, 2011).

Food production has further declined due to general land degradation where there is mining of nutrients without replenishment and cultivation of forestlands or vulnerable pasture lands leading to a reduction in soil quality (Oldeman, 2000).

Agricultural lands are most susceptible to degradation compared to non-agricultural lands. This shows that land use, associated inputs and management are the main causes of degradation (Nkonya *et al.,* 2011). The consequences of land degradation include a reduction in crop and pasture productivity, forest products such as timber and non-timber products; all of which are linked to poverty and food insecurity. Similarly, cropping systems are extended into marginal lands (Bai *et al.,* 2008).

2.1.1 Land Degradation in Kenya

In Kenya, 64% of the land is subject to moderate degradation, 21% to severe and 1.7% is severely degraded (Macharia, 2004). By early 2000, it was reported that approximately 30% of the country’s land area was severely degraded (UNEP , 2002). An estimated 12 million Kenyans (a third of the population) depend on the degraded land reportedly to be 65% agricultural land (Bai *et al.,* 2008).

Degradation of land in Kenya is a phenomenon increasing in severity and extent such that 20% of all cultivated areas, 30% of forests and 10% of grasslands are subject to degradation (Muchena, 2008). Potential areas for land degradation, defined by decline in net primary productivity and rain use efficiency occupy 17% of the country and 30% of its cropland. In agricultural context, land degradation is partially related to soil quality.

Soil degradation affects various aspects which include nutrient content, water holding capacity, rooting depth, acidity, salinity, porosity and soil biomass. The assessment of soil degradation has mainly been done through analysis of biological and biochemical functions. However, these factors do not predict the physical stability of degraded soils, which is a major function to deterioration of these soils with regard to water and nutrient storage and fluxes (Fairhurst, 2012). This is the main issue that has brought about PRS which pinpoints to degraded agro-ecosystems.

2.1.2 Poorly responsive soils as a consequence of land degradation

Evidence points to a fact that there are emerging cases of crops which do not respond in a significant way to addition of mineral fertilizers in some areas (Nziguheba *et al.*, 2010). Some scenarios of PRS occur in highly fertile soils which produce 3 t ha^{-1} or more while in other cases there are low yielding (< 1 t ha^{-1}) (Zingore *et al.*, 2007). Poorly responsive soils are those that lack an increase in yield after applying of N, P, K fertilizers; having a value cost ratio (VCR) of less than 2 (Njoroge *et al.*, 2017; Vanlauwe & Zingore, 2011). This problem is experienced by small scale farmers who do not benefit from fertilizer application yet the prices of these inputs tend to be high. Currently, little information exists on these soils hence their characteristics are not well defined and the extent of their occurrence in SSA hypothesized to be as high as 40 - 48% (Njoroge *et al.*, 2017; Vanlauwe *et al.,* 2010).

Processes linked to the occurrence of poor responsive soils can be divided into different categories:

i) Inherent soil properties. These are properties that do not change within a short period. They are long term and are related to the parent material of the soils in a particular area (Sanchez *et al.*, 2003). They include soil acidity, Al or other metals toxicities e.g. Mn or deficiencies.

The depth of the rooting zone is also an inherent factor. When soils are shallow, their response to fertilizer application can be low due to poor rootability. Also, soils which are made up of upper sand texture horizons tend to have a mineralogical composition of quartz, kaolinites and sesquioxides which makes them susceptible to crusting and compaction (Six *et al.*, 2000). Since inherent soil conditions cannot be changed, measures that improve their statuses such as the addition of nutrients and organic amendments can be adopted to improve their agricultural productivity.

ii) Inappropriate management practices over a long period of time. The problem of poor responsiveness could have risen from long-term inappropriate agronomic practices such as the long time use of acidifying fertilizers (for example, diammonium phosphate (DAP)), continuous cropping without replenishment of nutrients and lack of addition of organic manures; this is as reported in research studies in Western Kenya (Otinga, 2012; Okalebo, 2009). This has further led to changes in soil properties and processes; consequently, leading to the degradation of soils.

iii) Non-soil factors could also influence this problem of poor responsiveness. These factors include weather, crop pests and diseases.

Weather factors as relating to poor responsiveness could arise from little moisture held within the soils (Nziguheba *et al.*, 2011; Jaetzold *et al.*, 2005).

In order to nullify the factor of pests and diseases, Nzighueba *et al.*, (2011) proposed that poor responsiveness to be tested by cereal and leguminous crops where if the cereal crop was affected by pests and diseases; it would be unlikely that the leguminous crop would suffer the same.

iv) Some or all combinations of all the factors mentioned above.

Production constraints resulting from inherent soil factors, weather constraints, pests and diseases are easily identifiable by either direct observation or through tests. However, those related to soil degradation may not be readily known or easy to identify. The effect of soil degradation is revealed through physical, chemical and biological attributes of the soil (Stocking, 2006).

Physical degradation mainly results from the removal of vegetation which leads to exposure of soil to water and wind erosion. The loss of the topsoil and SOM consequently occurs leading to surface crusting which is common in sandy Nitisols (Valentin, Rajot, & Mitja, 2004). Also, excessive tillage is associated with soil compaction which restricts crop rooting and water infiltration (Hamza & Anderson, 2005).

Chemical degradation occurs in the reduction of nutrient stock in the soil. It occurs concurrently with a reduced cation exchange capacity (CEC) due to metal deficits created and is a precursor to soil acidification. It is further worsened by the application of ammoniacal sources of nitrogenous fertilizers without adequate applications of organic material (Otinga, 2012).

This leads to soil infertility with the varying magnitude of response to inputs which depend on the soil type, landscape position and farm management history (Zingore *et al.*, 2007; Stocking, 2003).

Biological degradation is observed in depletion of organic matter and reduced macro and micro-organisms. A clear example is seen in infestation of soil with *Striga hermonthica*, a parasitic weed on maize associated with low soil fertility (Kifuko-Koech, 2013). *Striga* attaches itself to the roots of maize from which it draws moisture and nutrients, inhibiting plant growth, reducing yields and in extreme cases causing plant wilting and death (Ndwiga *et al.*, 2013). In addition, low SOM pinpoints to low Carbon which in turn affects the number of micro-organisms in the soil (Murphy, 2014).

In an effort to rehabilitate poor responsiveness, Zingore *et al.*, (2007) illustrated that it took 3 years of FYM application of 19 – 26 t ha^{-1} for a sandy soil to have an observable response. Therefore, the study of phenomena encompassing degradation is important for the description of poor responsiveness in soils.

2.2 Physical drivers of poor responsive soils

2.2.1 Erosion risk

Approximately, 36% of the soils in the tropics are at high risk of erosion and this phenomenon negatively affects plant productivity and ecosystem functions. Included in this category are soils with sharp textural breaks (for example sandy over clayey), very steep soils (more than 30% slope) and shallow soils (depth of less than 50 cm deep) (Sanchez *et al.,* 2003).

Water erosion is an imminent global challenge in this century with adverse effects on within the site such as soil quality and agricultural productivity; and off the site such as siltation of water masses (Mengistu *et al.,* 2014). It affects sustainable agriculture in sloping lands where rainfall intensities are high (Halim, Clemente, Routray, & Shrestha, 2006). The reduction in soil quality and productivity hence affect the crop yield.

Any land use activity that interferes with vegetation cover and improper tillage practices along a slope leads to erosion. Erosion often results in a decrease of the soil supply functions in three ways; the removal of organic matter, the change in depth to a possible root-barrier and loss of structure leading to increased compaction (Elsheikh *et al.,* 2015). Particular losses of SOC and total N were reported to result in plant nutrient deficiencies, deterioration in soil structure, declined workability and reduced water-holding capacity (Afshar, Ayoubi, & Jalalian, 2010).

The risks are exerted on food security in developing countries due to inappropriate agricultural practices, the low adaptive capacity to restore degraded soils and replenish nutrients. In the economy of countries such as Kenya, where 80% of the people rely on agriculture, physical topsoil losses and nutrients removal exacerbate food security (Mengistu *et al.,* 2014). In a research conducted in East Africa, losses of soil due to erosion related to SOM reduction by 20% and 50% resulted in 17 t ha^{-1} per year and 19 t ha^{-1} per year, respectively with the latter exceeding the tolerance level of 18 t ha^{-1} per year; with extreme losses of 20 t ha^{-1} per year reported (Mengistu *et al.,* 2014).

2.2.2 Soil compaction

Soil compaction is viewed as a multi-disciplinary problem where heavy machinery, soil, crop and weather interactions play an important role and consequently affect agricultural production. Soil compaction is a physical form of soil degradation that alters the structure of the soil which is hard to locate and design an approach (McGarry & Sharp, 2003). This phenomenon involves the rearrangement of solid soil particles closer to each other thus increasing the bulk density.

The level of compactness of a soil is a measurable attribute that shows the ratio of the actual bulk density to with to the reference bulk density. This is obtained in a uniaxial application of force on a wet soil at a static pressure of 200kPa (Lipiec & Hatano, 2003). This aspect is studied as an indicator of soil quality. The alterations in soil structure resulting from mechanical stresses induce soil deformation, affecting water storage and availability, penetration resistance, heat and temperature fluxes and impairs aeration and tortuosity all of which interact and affect crop growth (Siczek, Horn, Lipiec, Usowicz, & Luwoski, 2015; Lestariningsih & Widianto, 2012).

Nawaz *et al.,* (2013) in a study to understand, quantify and predict effects of soil compaction came up with the major points that:

i) Moisture available, soil texture and the structure have a high influence on the level of compactness
ii) Compaction directly influences physical parameters such as bulk density, soil strength and its porosity and can therefore be used to measure compaction

iii) Compaction alteration on soil physical properties can alter the mobility of elements and change N and C cycles which favor greenhouse emissions in wet areas.
iv) Compaction when severe can lead to deformation of root as well as affect germination,
v) Macro- and micro-fauna are largely decreased by

The nature of weather patterns in the tropics is characterized by a short period of rainfall when it becomes easy to till farms and is conducive for compaction (Nawaz *et al.*, 2013), resulting in deeper stress penetration and subsoil compaction.

Porosity is reduced by 5.7% by an increase of 100kPa in sandy soils (Sakai, Nordfjell, Suadicani, Talbot, & Bøllehuus, 2008). Modification of the physical parameters was found to determine soil compaction influence on chemical properties (Jones, Spoor, & Thomasson, 2003).

It is reported that soil compaction correlated negatively with yield as they are not directly linked (Ishaq, Hassan, Saeed, Ibrahim, & Lal, 2001). However, they explained that it leads to reduced root growth, low nutrients access and their loss by leaching and runoff which in turn affect plant growth. Soil bulk density, strength, aeration, water, thermal and structural attributes are identified as main behavioral properties which influence the quality of the soil (Nawaz *et al.*, 2013). Infiltration rate may be used to show compaction as porosity is reduced; water infiltrates quicker in uncompacted soil (Silva, Barros, Costa, & Leite, 2008).

In a study in Western Kenya by Cebula (2013), a gap was identified for lack of increase of yield after fertilizer application, yet the topsoil bulk density was within optimum ranges (1.16 g cm^{-3}). Thus, bulk density analyses are not sufficient for studying soil compaction.

2.2.3 Penetration resistance

In an agricultural context, penetration resistance is subject to compaction and is determined by measuring the soil strength against penetration resistance. The soil strength decrease as soil moisture content increases (Nawaz *et al.*, 2013). Bouwman and Arts (2000) highlighted the necessity for being careful when measuring soil strength as moisture content varies in between the seasons.

Penetration resistance is measured in terms of cone resistance (megapascals (MPa)) which serves as an indicator of root penetration and root growth capabilities. A cone penetrometer with a 30° angle and a basal diameter of 4 mm is used to make penetrometer resistance measurements at a penetration rate of 2 mm per minute. Earlier, penetrometers were used to assess trafficability, but the recent application is for measuring roots penetration in soils (Whalley, To, Kay, & Whitmore, 2007). It was reported that that penetration resistance of greater than 3 MPa hindered elongation of roots in sandy textured soils as expressed in Figure 1 (Sinnett, Morgan, Williams, & Hutchings, 2008). Further, Whalley *et al.*, (2007), emphasizes that root elongation is significantly restricted at penetration resistance measurements larger than 2.5 MPa.

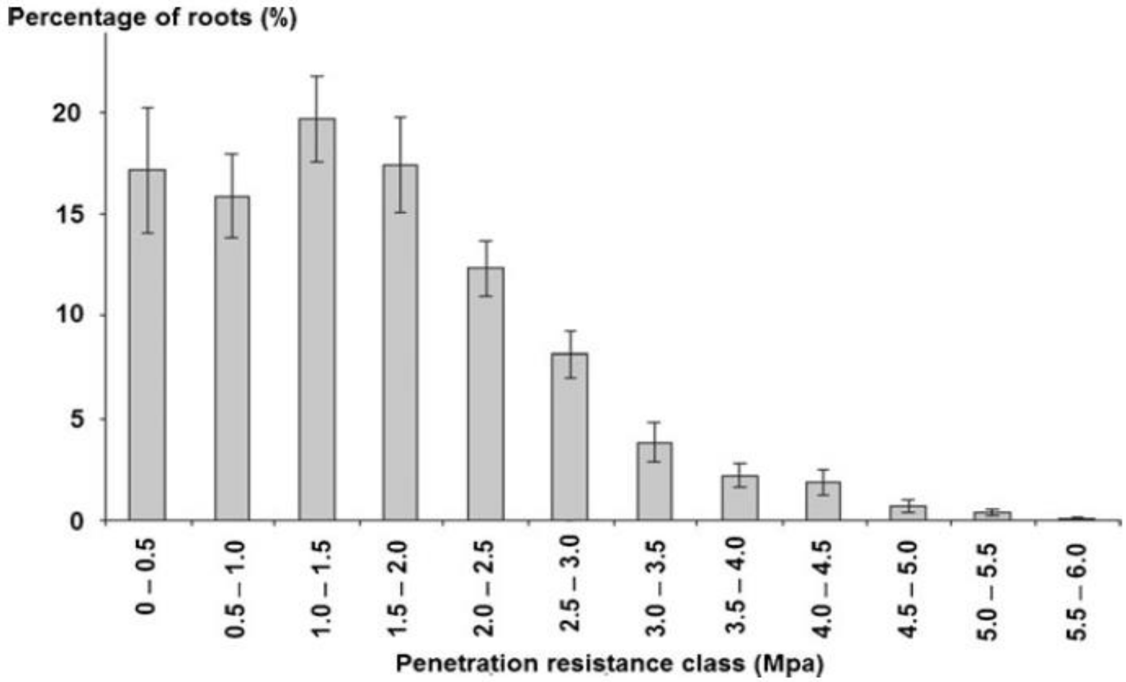

Figure 1: **Mean percentage of roots in each penetration resistance class using the penetrometer; 90.7% of roots are present in the penetration resistance class less than 3 MPa.**
(Source: Sinnett et al., 2008)

However, Hazelton and Murphy (2007) indicated how root growth can be hindered before the critical value of resistance is reached.

The broad interpretations were:

- <1 MPa at field capacity and drier – These are the optimal root growth conditions and physical fertility is optimum
- 1 to 2 MPa at field capacity – seedling emergence is retarded and fails if no cracks are present, root growth is restricted as resistance is likely to reach 3 MPa as the soil dries. Physical fertility is moderate.

- 2 to 3 MPa at field capacity – root growth is impeded and restricted to old root channels and cracks. Water and nutrient uptake are restricted. Physical fertility is poor.

Most studies on penetrometer resistance describe its dependency on soil physical properties such as water content, density and matric potential (Whalley *et al.*, 2007). In some instances, properties that change with time such as particle size and organic matter content are included (To & Kay, 2005). Air porosity required for root growth has been suggested as 15% (Dexter & Zoebisch, 2002). However, soil depth studies in relation to effects of penetration resistance are excluded. Increasing depth results in higher resistance to penetration, due to overburden pressure and internal friction. Soil depth is thus usually ignored since it is not a treatment factor in these studies (Gao, Whalley, Tian, Liu, & Ren, 2016).

2.3 The role of rooting depth role on crop growth and yield

Plant rooting depth refers to the maximum accessible depth in the soil stratum with no barriers that may inhibit crop root elongation which relies on the type of crop and properties of the soil (Yang, Donohue, & McVicar, 2016). This zone is largely influenced by pH, compaction and water table depth. It is reported that 80 – 90% of access of water and nutrients for crop requirements happens in this zone (Imark & Rudnick, 2014). In addition, the plant rooting depth is recommended for sampling of soil nutrients analysis and determination of plant available water (PAW) (Irmak & Rudnick, 2014). This parameter thus plays an essential role in determining the active soil zone which controls water movement back to the atmosphere through plant transpiration (Yang *et al.*, 2016).

It therefore largely affects the exchange of energy and carbon between land and atmosphere resulting from a close linkage between terrestrial water, energy and carbon cycles (Yang *et al.,* 2016). In addition, it is necessary for studying water drainage and run-off patterns. However, this parameter is predominantly undisclosed due to technical issues involving its direct measurements (Narayanan, Mohan, Gill, & Prasad, 2014) with only representatives of several plants being known.

Direct measurement approach is biased and does not represent global distribution of rooting patterns. Also, deep -rooted plants are practically harder to measure directly. The reliability of constructed statistical relationships in predicting rooting depth from direct measurement are thus dependent on location and soil properties; hence they are not true representatives. Inverse modelling and model calibrations (especially hydrological models) are then used to indirectly estimate this parameter (Yang *et al.,* 2016).

Particularly, the characteristics of roots are crucial for soil exploration and uptake of water and nutrients. During drought period, deep root systems aid the plants to avoid water stress by accessing water in deeper horizons (Narayanan *et al.,* 2014). Maize has a complex rooting system consisting of primary and seminal roots formed shortly after germination and shoot-borne and lateral roots initiated later in crop growth (Hochholdinger, Marcon, Baldauf, & Frey, 2018). Maize crop has an effective rooting depth of 90 – 120 cm (Irmak & Rudnik, 2014). This manifests in maize grown in shallow tilled soils (< 20 cm) (Alamouti & Navabzadeh, 2007) with physical or chemical restraints (such as compaction and low or high pH) (Irmak & Rudnik, 2014) having low yields such as in Western Kenya (MOA, 2014; Jaetzold *et al.,* 2005).

2.4 Soil water availability as a constraint in PRS

Hydraulic properties analyses are used in the evaluation of soil water; they include infiltration, conductivity, storage and plant-water relationships. The definition of soil water effects requires an estimation of soil water characteristic for water potential and hydraulic conductivity (Saxton & Rawls, 2006). Soil water content is expressed in terms of either mass or volume (θm or θv). A soil water characteristic curve is used to describe the amount of water held under equilibrium at a given matric potential.

Matric potential is a term used to describe the energy status of water by referring to the amount of energy required to bring water from a certain state to a reference state. Matric potential tends to extend over several orders of magnitude for a range of water contents (which lie between saturation and permanent wilting point water content), hence it is plotted on a logarithmic scale.

Thus, the soil water characteristic curve (SWC) is an important hydraulic property that relates to size and connectedness of the pore spaces. This parameter is affected by soil texture and structure; and SOM (Tuller & Or, 2003). Figure 2 shows representative SWC curves for different textures, showing the effects of porosity and variation in slopes of the relationships resulting from variable pore distributions.

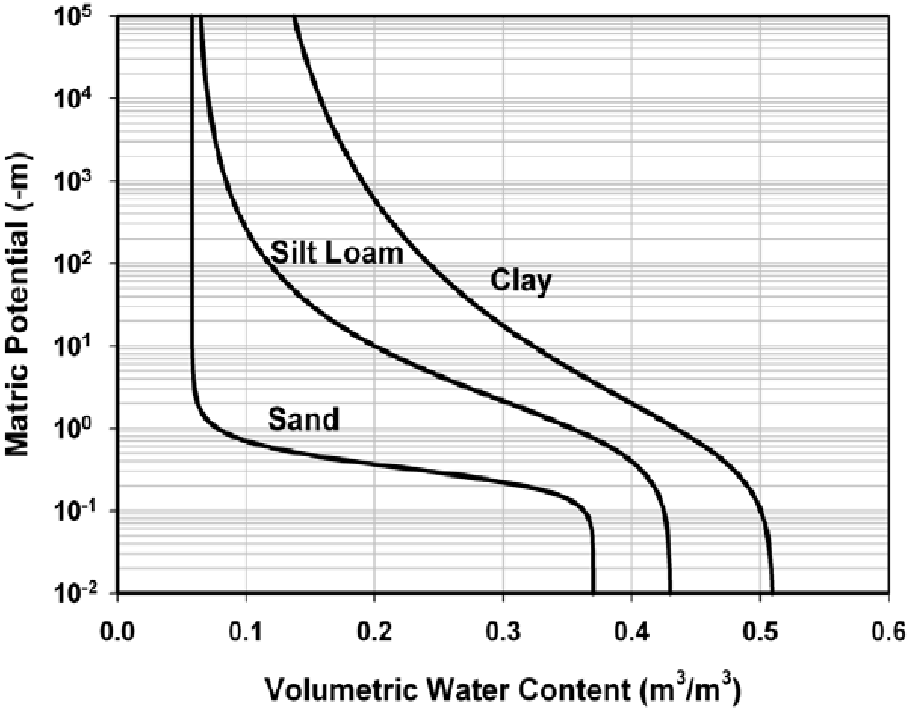

Figure 2: Typical soil water characteristic curves for soils of different textures.

(Source: Tuller and Or, 2003)

Water tends to be a limiting factor in rain-fed crop production systems as is the case of tropics, this results from low precipitation and/or uneven inter-annual distribution (Fernandez-Ugalde, Imaz, & Virto, 2009). This occurs in regions with dry seasons which are longer than 3 months.

A constraint is posed to the cultivation of year-round crop in 60% of soils in the tropics. Particularly in the Western region of Kenya, that has a bi-modal rainfall pattern with a consistent dry period from May to September and December to March annually, respectively (Jaetzold *et al.,* 2005). Zingore and Johnston (2013) observed that drought stress is a key factor that affects food production.

Hydraulic properties of soils vary in space and time due to natural and human influences. Accurate description of these properties is necessary for describing soil processes such as rainfall infiltration, runoff and recharge of an aquifer, nutrient movement through a soil profile (Bagarello, Castellini, & Iovino, 2005). The documentation on effects of cultivation on soil hydraulic properties has been done in recent decades; however, the results remain unclear and show inconsistencies across locations, soils and agricultural practices (Strudley, Green, & Ascough, 2008). In addition, soil physical properties, which influence hydraulic properties, change with environmental conditions such as rainfall or drought. Hydraulic conductivity tends to increase with tillage and decrease along the crop growing season as the soil structure settles and soil particles repackage themselves.

Soil water retention is used to express plant available water by predicting soil water storage capacity. The dynamics of this parameter within tilled systems is not well studied and understood (Jirku, Kodesova, Nikodem, Muehlhanselova, & Zigova, 2013). Most methods for field soil water measurements are time-consuming and expensive; and thus modeling approach is used. However, most models do not take into account the temporal dynamics of soil properties as it assumes all physical properties are constant (Alletto *et al.*, 2015). These models are unable to show actually measured water contents in some instances, making over- or under-estimation.

2.5 Dimensions of Soil Organic Matter

Soil organic matter includes plant and animal materials in various stages of decomposition. Most SOM is found on the topsoil rather than deeper horizons (Cooperband, 2002).

Since SOM is viewed as the link between physical, biological and chemical aspects of soil, it is associated with various functions. They include (Cooperband, 2002): -

i) Stores and supplies nutrients (both macro and micro); and increases of cation exchange capacity
ii) Stabilizes soil particles by holding them together as aggregates
iii) Assists soil to resist compaction, promote water infiltration and reduces runoff
iv) Improves water retention and porosity
v) Improves workability as the soil is more friable
vi) Provides Carbon and energy to microbes
vii) Reduces negative effects of pesticides, heavy metals and other pollutants

SOM is measured in terms of SOC with a general conversion factor of 1.72 (Murphy, 2014). Murphy (2014) classified SOM into three distinct types:

- Labile fraction (Active fraction) consisting of decomposing plant residues and fine roots is not stable and hence the turnover period is short; less than 1 year to 2 years.
- Humic fraction (stable fraction) which is an active entity including partially stabilized organic matter and has a turnover period of 5 to 25 years
- The resistant fraction which is most stabilized chemically and/or physically with a turnover period of 250 to 2500 years

However, researchers view this division as largely conceptual since it has been difficult to define them in measurable pools (Sanchez *et al.,* 2003; Six & Jastrow, 2002).

Particulate organic carbon (POC) is the generally preferred estimate of the labile SOM fraction (Murphy, 2014). Active SOM fraction is closely associated with nutrient supply (Cooperband, 2002) and development of soil macroaggregates (Murphy, 2014). Organic amendments applied supply plant nutrients such as N, P and K. For instance, N applied by FYM is estimated at 25 – 40% of the total N content while that of compost is estimated at 10% or less (Cooperband, 2002). The stable recalcitrant SOM (humic fraction) is associated with CEC.

Soil organic matter has a negative charge which improves soil fertility by preventing leaching of plant nutrients into lower horizons which are inaccessible to the plant. Plant micronutrients such as copper (Cu) and Zn are chelated by SOM and supplied in a plant available form. In low pH soils, SOM chelates excesses of Al and Fe ions which bind nutrients such as P and make them unavailable for crop growth. Loveland and Webb (2003) reviewed the critical threshold value for SOM in agricultural soil and concluded as at 2% SOC. Most soils are reported to fall below 1% in agricultural systems in Kenya (MOA, 2014; Jaetzold *et al.,* 2005). In addition, researchers in the tropics have also pointed out that in order to curb the nutrient deficits, practicing integrated soil fertility management (ISFM) which involves the addition of mineral fertilizers and organic resources are of key importance (Keino 2015; Otinga, 2012; Vanlauwe *et al.,* 2010, Zingore *et al.,* 2007). There is a lack of clear results as to the thresholds levels of SOC levels that define the point at which processes become dysfunctional in soil and affect plant growth.

2.5.1 Role of SOM on soil physical quality and consequently rehabilitation of PRS

Different SOM fractions are responsible for the stability of different aggregate sizes. Macroaggregates stability (>250 µm) depends on the active fraction. Micro aggregates stability (250 µm to 20 µm) is associated with the humic fraction and smaller micro-aggregates (20 µm to 2 µm) are determined by relative percentages of K, Na, Ca and Mg (Murphy, 2014). The overall stability of aggregates is very dependent on stable micro-aggregates; which in turn is important for the development of macroaggregates (Krull, Skjemstad, & Baldock, 2004).

Kay and Angers (1999) reported a rapid decline of aggregate stability as SOC decreased from 1.5% to 1.2%. Further, they reported that a level of 2.0% SOC is a critical threshold for maintenance of stable aggregates. Carter (1992) indicated that 4.0% SOC gives the maximum aggregate stability. Aggregate stability is not a soil property that can be assigned to soil functions as can be done for others like pH, infiltration and bulk density. It relates to functional soil properties such as bulk density, soil strength and water holding capacity (Murphy, 2014).

Bulk density is strongly correlated to SOM. High levels of SOM lower bulk density by increasing porosity. However, bulk density is affected by other soil properties such as soil texture, clay mineralogy, sodicity, exchangeable cations, and sesquioxides. Land use history may affect bulk density through cultivation, time since cultivation and amount of rainfall experienced and compaction by livestock or machinery (Murphy, 2014).

Relationships have been created between bulk density and SOM; where the following equations were derived (Valzano, Murphy, & Koen, 2005):

$$Bulk\ density\ (Bd) = 1.608 - 0.0672 * SOC \qquad \text{Equation 1}$$

Arguably, changing bulk density by solely increasing SOM is not likely to improve crop production. This is because higher bulk densities may occur than those predicted using equations and many other physical properties (soil strength, friability, susceptibility to erosion or water holding capacity) which are not directly accounted for by measuring bulk density may be limiting crop production.

In studies of soil hydraulic properties, plant available water (PAW) is the most important factor in crop production. PAW refers to the difference between field capacity (FC) and permanent wilting point (PWP). Water availability at FC and PAW vary widely between soils and are determined by various factors which include texture, cation characteristics, sesquioxides and most importantly organic matter content.

Hudson (1994) analyzed the effect of SOM on water holding capacity for soils with specific textures. His findings were that water held at FC had a rapid increase with an addition in SOM content rather (by 3.2%) while that of PWP was 0.92% per 1% increase in SOM for sandy soils. Silt loamy textured soils had the changes; a 4.5% increase in 1% increase in SOM for FC and a 0.8% increase in PWP for a 1% increase in SOM. A rather interesting discovery was made from results for sands, loamy sands and sandy loam textures (Rawls, Pachepsky, Ritchie, Sobecki, & Bloodworth, 2003).

When the SOC levels were higher than 2.1%, moisture content at FC was predicted by SOC with 4.8% and 7.7% critical values while those with less than 2.1% SOC were predicted by texture.

Loamy and clayey soils have FC predicted by texture mainly. Krull *et al.,* (2004) reported that an increase in 1% SOC influenced water holding capacities by the following amounts:

- Soils with less than 10% clay content have water holding capacity increase by 20 to 30%
- Soils with 10 to 15% clay content have water holding capacity increase by 10 to 25%
- Soil with 15 to 20% clay content have water holding capacity increase by 10 to 18%
- Soils with more than 20% clay content have water holding capacity increase by about 10% or less

Murphy (2014) reported SOC from 0.7% to 3.0% as the general operational level in dryland agricultural soils.

Soil organic matter increases infiltration rate by providing aggregate stability to wetting and raindrop impact. Surface crusting and runoff are therefore minimized. This, in turn, ensures that water is stored in the soil for crop use. It also demonstrates that it is necessary to get different SOM fractions (Bell, Moody, Yo, & Connolly, 1999).

Active SOM fraction was reported to minimize friction at a level of 0.79 to 1.32 g of C per kg of soil in areas with rainfall intensity of 19 mm h^{-1} while 3.19 to 3.85 g of C per kg of soil was required for areas with 113 to 139 mm h^{-1}. This corresponds to 1.26 to 1.75% and 3.50 to 4.12% SOC respectively.

Soil strength is another factor that is largely affected by SOM. A relationship between penetration resistance to moisture content, bulk density and SOM is explained in the following equation (Kay, da Silva, & Baldock, 1997).

$$PR = c\,\theta^{d} BD^{e} \qquad \text{equation 1}$$

Where: PR is Penetration resistance

θ is Moisture content

BD is Bulk density

Coefficients c, d and e are functions of clay content and SOC

$$log_{e}c = -3.67 + 0.765\ (SOC\%) - 0.145\ (clay\%) \qquad \text{equation 2}$$

$$d = -0.481 + 0.208\, SOC\% - 0.124 clay\% \qquad \text{equation 3}$$

$$e = 3.85 + 0.0963\ (clay\%) \qquad \text{equation 4}$$

While working on a set of soils, Kay *et al.*, (1997) reported that a general increase of 1% SOC halved the soil penetration resistance, especially at moisture contents that fall below

FC. This reduced the resistance to a level below 2 MPa which is conducive for root growth.

2.6 Maize production in Kenya

Maize (*Zea mays*) is an important cereal crop; ranking third in the world after wheat and rice (Ali *et al.,* 2013). Maize grains are used for human and livestock consumption. In Kenya, maize is the staple food; contributing to 3% gross domestic product (GDP), 12% agricultural GDP and 21% of the total value of primary agricultural commodities (GOK, 2002). It is grown as a subsistence and commercial crop on an estimated 1.4 million hectares by large scale farmers (25%) and smallholders (75%) (De Groote *et al.,* 2005).

The annual production is reported at 2.4 million tons. On average, it is estimated that a person should consume 103 kg per year, however, with the current production, they consume 79 kg per person, showing a deficit in production (Pingali, 2001) . This deficit creates a need for importation. Maize production decline in Kenya began in the late 1970s (De Groote *et al.,* 2005) and has currently reached a level of less than 1 t ha^{-1} (MOA 2014; Jaetzold *et al.,* 2005).

An increase in maize production in Kenya is necessary. This is to be achieved through the adoption of new technologies which include the use of improved varieties and use of fertilizers. Njoroge *et al.,* (2018) reported that the use of secondary macronutrients and micronutrients improved maize yield in poorly responsive soils. This was observed when fertilizer applications with Ca, Cu and Zn increasing maize yield in Western Kenya. Farmers are however not taking up these technologies due to lack of benefits associated with their application and their high cost (Vanlauwe & Giller, 2006; De Groote *et al.,* 2005); this is more so amongst small scale farmers of Western Kenya.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Scope of the study

The regions for the study were Busia-North and Bungoma-Southwest. The site selections relied on the hypotheses that PRS occur in fields that have more than 50% sand and a slope of greater than 5%. Both macro- and micro-nutrients deficiencies had been observed with P, Ca, Zn and Cu levels falling below the critical crop requirement amounts (Njoroge *et al.,* 2017). Hence, traditional sole NPK application had no significant effect on the crops grown. Instead, a different approach of adding all deficient nutrients was recommended. This particular study observed whether after application of N, P, K, Ca, Zn and Cu significantly increased maize grain yield and the influence of the applied amendments in their organic and inorganic nature on selected physical characteristics.

3.2 Geographical and Climatic characteristics of the study area in Western Kenya

3.2.1 Busia Region

Busia lies between latitude 00°27’11” N and longitude 34°07’30” E. This area receives bimodal rainfall. The first season is from March to July and the second season from September to December. The annual rainfall amount range is 230 – 800 mm (Jaetzold *et al.,* 2005). The annual average temperature is between 21 - 22.7 °C (Jaetzold *et al.,* 2005). The annual potential evapotranspiration is between 1800 – 2030 mm with the having an elevation of 1200 m above sea level.

Busia county has a complex of imperfectly drained to poorly drained, low activity clays and the soils are classified as gleyic Acrisols (Jaetzold *et al.,* 2005). The main economic activity of the people is subsistence farming with land ownership averaging 0.16 ha. The main crop grown in this region is maize; while sorghum and millet are the alternatives. The dominant legumes in order of importance are beans, groundnuts, simsim, cowpeas and soybeans. (Jaetzold *et al.,* 2005).

3.2.2 Bungoma Region

Bungoma lies between latitude 00°34’00” N and longitude 34°34’00” E. This area receives bimodal rainfall; the first season starting in March through July while the second season occurs between September and December. The annual rainfall range is 1000 - 1200 mm with average annual temperature of about 21 – 22 °C (Jaetzold *et al.,* 2005). The annual potential evapotranspiration in the area ranges from 1400 mm to 1800 mm (Jaetzold *et al.,* 2005) and is elevated at 1385 m above sea level. Soils in Bungoma are defined as well drained, moderately deep to very deep partly stony or petroferric and classified as orthic and humic Acrisols and ferralic Arenosols (Jaetzold *et al.,* 2005). Agriculture is the main economic activity of the people of this region with sugarcane being the main cash crop. Maize is the dominant crop followed by sorghum, finger-millet and cassava. Legumes grown in order of importance are beans, pigeon peas and cow peas (Jaetzold *et al.,* 2005).

3.3 Experiment establishment and treatment description

3.3.1. Selection and identification criteria for the experimental sites

The experiment was set up on eight farmers' fields; four per each region. The farmers' fields deemed to be poorly responsive in Busia-North and Busia-Southwest, were selected and assigned codes as shown in Table 1.

Table 1: Specific location of selected farmers' fields and assigned codes

Region	Site Code	Sublocation	Village	Soil type	Depth
Busia-N	BUS01	Okuleo	Okuleo-C	Gleyic Arenosols	Deep
	BUS02	Akolong	Kutuku	Plinthic Arenosols	Shallow
	BUS03	Kekalet	Akichelesit	Plithic Acrisols	Shallow
	BUS04	Rwatama	Apokol	Plithic Acrisols	Deep
Bungoma-SW	BUN01	South-Bukusu	Lumboka	Stagnic Luvisols	Deep
	BUN02	South-Bukusu	Lumboka	Plinthic Acrisols	Shallow
	BUN03	Lunao	Lunao-A	Ferric Alisols	Shallow
	BUN04	Namatotoa	Khelea	Eutric Cambisols	Deep

N denotes North while SW denotes South-West. BUS denotes Busia-North, BUN denotes Bungoma-Southwest. Deep means the field could be augered up to > 20 cm while Shallow could not (< 20 cm).

In Busia-North, farmers' fields, BUS01 and BUS02 were classified as a gleyic Arenosols and plinthic Arenosols respectively. Arenosols comprise sandy soils due to weathering of quartz-rich sediments and rocks. They have a coarse texture with high permeability and low water and nutrient retention capacity.

Gleyic characteristics are identified by mottling where Iron is reduced to Fe^{2+} ions which have a greyish black color. This occurs in areas with stagnant water. Plinthite is a soil layer with hard nodules or hardpan which is impenetrable due to the strong bonds of kaolinite, quartz and other constituents. It is high in iron and low in humus (WRB, 2006).

The field, BUS01was classified as deep due to the ease at which it was easy to auger up to 40 cm. The plinthic layer in BUS02 created a hardpan which resulted in this site being classified as shallow (<20 cm). The other 2 fields, BUS03 and BUS04 were plinthic Acrisols. A plinthic layer is formed as a result of strong bonds between mainly iron, kaolinite and quartz which form an impenetrable hardpan. Acrisols have a higher clay content in the subsoil than topsoil due to eluviation processes; the clay type is low activity. BUS03 was classified as shallow due to a hardpan created by plinthite. The field, BUS04 was, however, penetrable as the plinthite formed occurred deeper (> 40 cm) in the soil profile and it was categorized as deep.

The farmers' fields selected in Bungoma-southwest region were as follows. BUN01 was a stagnic Luvisols: stagnic properties are those with 100 cm of the soil having reducing conditions (waterlogging) for some time during the year. Luvisols have argic subsoil horizon due to higher clay content being located subsurface; the clay activity is high and with high base saturation at some depths. This field had deep soils which could be sampled up to 40 cm. The field, BUN02 was a plinthic Acrisol which had similarities at the aforementioned BUS03 and BUS04. The third field in Bungoma-southwest, BUN03 was a ferric Alisols.

Ferric layer forms from strong weathering forming sesquioxides which are oxides of iron, aluminium and manganese; they form concretions with a reddish yellow coating. Alisols have a higher clay content in the subsoil than in the topsoil as a result of eluviation. They have a low base saturation and high activity clays throughout the argic horizon. The ferric layer with concretions hindered the movement of the soil auger and it was thus classified as shallow.

The fourth selected field, BUN04 was classified as a eutric Cambisols. Eutric layer has a base saturation of 50% or more between 20 and 100 cm. Cambisols are referred to as ‘young soils. They have at least clear differentiation of subsoil and transformation of parent rock is clear from structure formation. The soils were penetrable when sampled; thus, they were categorized as deep.

3.3.2 Description of fertilizer treatments applied in the study

In this study, three fertilizer treatments were used as seen in Table 2. Fertilizer treatment 1 was absolute control (without fertilizer application). Fertilizer treatment 2 was built on fortified FYM with Urea and Triple superphosphate (TSP). Fertilizer treatment 3 was a pure inorganic fertilizer comprising Mavuno fertilizer blend fortified with Urea, Muriate of Potash (MOP), Copper and Zinc sulfates. The targeted nutrient applications were 100 kg ha^{-1} N, 30 kg ha^{-1} P, 60 kg ha^{-1} K, 3 kg ha^{-1} Cu and 3 kg ha^{-1} Zn. However, the micronutrients; Zn and Cu were low in fertilizer treatment 2 since it was purely sourced from FYM and they were not topped up. This owes to the fact that organic amendments improve crop responses to micronutrients uptake from the soil.

Table 2: Fertilizer sources and the nutrient rates as used in the study

Type of Nutrient	**Quantity supplied by the fertilizer treatment**	**F.T.1**	**F.T.2**			**F.T.3**				
		None	FYM	Urea	TSP	Mavuno blend	Urea	MOP	$CuSO_4$	$ZnSO_4$
N (kg/ha)	100	-	17	83	-	27.4	72.6	-	-	-
P (kg/ha)	30	-	24	-	6	30	-	-	-	-
K (kg/ha)	60	-	60	-	-	22.5	-	37.5	-	-
Cu (kg/ha)	3	-	0.3	-	-	-	-	-	3	-
Zn (kg/ha)	3	-	0.2	-	-	-	-	-	-	3

F.T.1 denotes fertilizer treatment 1 which was Absolute control, F.T.2 is fertilizer treatment 2 (combination of organic and inorganic fertilizers) and F.T.3 is fertilizer treatment 3 sourced from pure inorganic fertilizers. Nutrients applied from FYM 6 t ha^{-1}, Urea 46:0:0, TSP 0:46:0, Mavuno blend 10:11:8; was selected due to array of nutients, MOP 0:0:50, Cu 25%, Zn 23%.

3.3.3 Detailed description of nutrient sources

Farmyard manure (FYM) was acquired from the University of Eldoret farm. This was to ensure uniformity in nutrients applied and source. A test was at the onset of the study in March 2015 to find out the nutritional content of the manure as shown in Table 3.

Table 3: Nutrients content in FYM used in the study

Parameter	Value
N (%)	0.27
P (%)	0.40
K (%)	2.06
Ca (%)	0.28
Mg (%)	0.18
Mn (mg kg^{-1})	0.03
Na (mg kg^{-1})	1.10
Fe (mg kg^{-1}**)**	3670.03
Cu (mg kg^{-1})	30.66
Zn (mg kg^{-1})	51.66
Carbon (%)	5.33
C: N	19.7:1

The table consists of nutrients analyzed in FYM sourced from University of Eldoret

Testing of FYM before application is necessary to find out the levels of nutrients; after this, topping up of nutrients to sufficient levels using inorganic fertilizers can be done appropriately. This is recommended to farmers, whose FYM differs due to improper storage and is mostly of poor quality.

Urea fertilizer of nutritional content 46:0:0 was used to supply N. It was applied at a rate of 81 and 72 kg of Urea ha^{-1} in fertilizer treatments 2 and 3, respectively. Triple superphosphate (TSP) is a straight fertilizer of formula 0:46:0 was used to supply P. The rate applied was 30 kg of TSP ha^{-1}. Mavuno is a compound fertilizer blend consisting of an array of plant essential nutrients unlike most of other fertilizers.

The main nutrients considered in this study while using Mavuno were 10% N, 11% P, 8.3% K, 5.7% Ca and 3% Mg. The rate of applied was at 273 kg of Mavuno ha^{-1}. Muriate of potash (MOP) is a straight fertilizer made up of chloride of potassium. It consists of

60% potash. In this study, this was used to supply K in addition to that of Mavuno fertilizer.

It was applied at a rate of 75 kg of MOP ha^{-1}. Copper sulfate consisting of 25% Cu was used to supplement the essential micronutrient. It was applied at 12 kg of Copper sulfate ha^{-1}. Zinc sulfate consisting of 23% Zn was used to supply the essential plant nutrient. It was applied at rate of 14 kg of Zinc sulfate ha^{-1}.

3.3.4 Experimental design and layout

The experiment as show in Figure 3 was laid out in a randomized complete block design (RCBD). Each site had three fertilizer treatments which were replicated thrice. This gave a total of nine plots. The plot sizes were 5 m by 4.5 m with the crop planted on the length side. The blocks were set up across the slope gradient. The crop was planted against the slope to ensure minimal loss of nutrients and soil. The distance between blocks was 1 m and 0.5 m between plots.

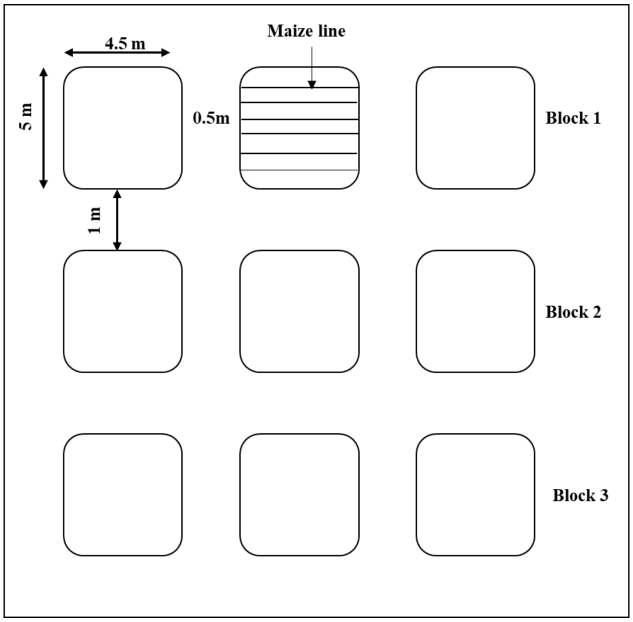

Figure 3: A schematic representation of the experimental layout showing blocks and distances as it was set up on the sites. The rectangles represent the actual plots.

3.4 Test crop

Maize (*Zea mays*) hybrids H516 and H513 series were acquired from Kenya Seed Company and planted in LR and SR 2015 respectively, due to its suitability for the selected agroecological zone. These varieties are early maturing (3 months) hence do well in areas receiving short duration of rainfall. The maize seeds were planted at a spacing of 75 cm within rows and 25 cm between plants. A total of 6 lines were planted in each plot.

3.5 Maintenance of experimental sites

Two seeds were sowed and thinned to one plant per hole, two weeks after germination to ensure uniformity and meet target plant population of 44,444 plants per hectare. Weeding of the plots was done twice in each season to ensure weed free environment for maize.

Prior to planting of maize seeds, all other forms of fertilizer were applied in single application while N was applied in splits. The first application (50 kg N ha^{-1}) was made during planting. While of the remainder 50 kg N ha^{-1} was used as a top- dress one and half months after planting, after the second weeding.

3.6 Disturbed soil sampling

Initial soil sampling was done using the grid method prior to nutrients application for analysis of inherent physical and chemical attributes following described procedures by Okalebo *et al.*, (2002). The disturbed soil samples were taken using an auger from three random spots from each block. A total of nine samples were obtained and mixed thoroughly into composites sample of 500g. This was done per site.

The samples were later air-dried at the University of Eldoret’s greenhouses and sieved through a 2 mm mesh. The samples were analyzed for selected physicochemical properties.

Plate 1: Disturbed soil sampling depth and sample packaging as carried out in the field

(Source: Author, 2015)

3.7 Laboratory Procedures used to analyze various physical characteristics

3.7.1 Procedure for the analysis of soil texture

The analysis of soil texture was done using the procedure as described in Okalebo *et al.*, (2002) in the University of Eldoret Soil Science laboratory. Air dried and 2 mm sieved soil of 50 g was weighed. The soil was then saturated with distilled water and Calgon (sodium hexametaphosphate 10 ml) added. It was left to stand for ten minutes then it was transferred into a dispersing cup and filled up with water.

The dispersing cup was placed in an electronic stirrer for two minutes. Then it was transferred into a graduated cylinder with the remaining soil rinsed. A hydrometer was placed into the graduated cylinder and water filled to the 1130 ml mark after which it was removed. The cylinder was inverted 10 times while covered again. After 20 seconds the hydrometer was placed inside. At the 40th second, the hydrometer reading was taken and temperature recorded with a thermometer. The suspension was inverted ten times again and allowed to stand for two hours without disturbance. Hydrometer and thermometer readings were taken and recorded. Temperature corrections were done on the hydrometer readings. Calculations for the different particles were as follows: -

Percent Sand = (50 g – First Reading)/50 * 100

Percent Clay = Second reading/50 * 100

Percent Silt = 100 - (% Sand +% Clay)

Key words: First reading refers to the initial hydrometer reading at 40 seconds. Second reading refers to the latter hydrometer reading after 2 hours

3.7.2 Procedure for the analysis of stable aggregates

The procedure was adopted from Soil Service of Belgium (2014) and conducted in KU - Leuven, Division of Soil and Water Management laboratory. Four grams of dry soil sample was sieved and then placed in distilled water for five minutes, until saturated. Water (100 ml) was poured into an Aluminum cup which was then placed on a wet sieving apparatus.

The soil was sieved by up and down motion in the water for three minutes. Then, 100 ml of Calgon solution (2 g of Calgon in 1 L distilled water) was poured into a stainless-steel sieving cup. The same sample was sieved in Calgon solution for 15 minutes until the fragment remaining on the sieve consisted of sand and organic material which were disposed. The cups were placed in an oven at 105 °C until the soil dried up then weighed. The weight of water sieved soil was named Weight A and that of Calgon sieved as Weight B. The percent stable aggregates (S.A) were calculated as:

$$\text{S.A. (\%)} = \text{Weight A} / (\text{Weight A} + \text{Weight B}) * 100$$

Key words: Weight A refers to weight of water sieved soil.

Weight B refers to weight of Calgon sieved soil

3.7.3 Procedures for determination of soil moisture characteristics

Procedure for determining moisture availability at field capacity

One kg of air-dried soil was weighed per site into pots replicated twice. Water was poured into the soil until it leaked from the base of the pots. After one hour, the procedure was repeated. This was to ensure that the soil was draining freely. A polythene bag was placed on the top of the container and holes were made. The containers were left in the greenhouse for 48 hours. The weights of the containers were recorded (Weight A). The difference of the container with contents, the soil and container itself were calculated in order to give a water content of the soils at field capacity (FC) (Okalebo *et al.,* 2002). This was expressed as: FC = Weight A – (Soil + Container Weights)

Key word: Weight A refers to the total weight of container plus contents (water and soil)

Procedure for determining moisture availability at permanent wilting point

Permanent wilting point (PWP) of these soils was modeled using Obi, Obi, & Onweremadu, (2012) procedure. Two maize seeds were planted per pot at field capacity. After germination, the seeds were thinned to one. A plastic cone of about two cm diameter and three cm length was placed around the plant to a depth of 2.5 cm in the soil. Silicon glue was smeared from the outer region of the ring to the pot covering the soil. This was to ensure that moisture was not lost through evaporation from the soil. Upon wilting of the plant, the soil sample was taken from the container and weighed (Weight A). The sample was oven dried at 105 °C for 48 hours and weighed again (Weight B).

The permanent wilting point was expressed as a percentage of differences between the weights divided by the weight of the oven dried soil with the equation: PWP = (Weight A – Weight B) / Weight B * 100

Key words: Weight A refers to the weight of soil sample immediately after plant wilting

Weight B refers to the weight of oven dried soil sample

3.8 Field Based analysis

3.8.1 Procedure for testing soil's infiltration rate

The soil was pre-wetted to saturation using five liters of water for 20 minutes. A metal ring of ten cm diameter by 30 cm height was driven into the soil up to five cm depth within each treatment plot. A 30 cm ruler was placed within each ring.

Water was poured into the tube up to 25 cm reading on the ruler. After five minutes, the level to which the water in the tube had moved was noted on the ruler and recorded. This was followed by topping up of water to 25 cm again. This step was repeated thrice. After, readings were recorded at an interval of 20 minutes thrice (Cebula, 2013). The average of the last three readings of 20 minutes interval was recorded as the infiltration rate. This was done at vegetative stage of the crop during LR and SR.

Plate 2: Demonstrations of infiltration measurement in the field using a PVC pipe to mimic single-ring infiltrometer

(Source: Author, 2015)

3.8.2 Procedure for testing soil compaction

Penetration resistance was tested when the soils were at field capacity when it had rained continuously for a week and rainfall event having occurred not less 24 hours (Duiker, 2002).

This was to ensure that over readings were not made when soils are dry as the penetration resistance increases and vice versa. A proving ring penetrometer was pushed into the soil. Readings were recorded at three depths (10 cm, 20 cm and 30 cm) twice per plot. After recording the PR reading made at ten cm, the top soil (up to 10 cm depth) was removed with an auger; and consequently, repeated at 20 cm and 30 cm depths. This was done to avoid overreading resulting from friction between the soil and cone. The readings were recorded in pounds per inch (PSI) then later converted into units of (MPa) in one PSI equals to 0.0068948 MPa. This was done at vegetative stage of the crop during LR and SR.

Plate 3: Measuring penetration resistance using a proving ring penetrometer

(Source: Author, 2015)

3.8.3 Maize grain yield harvest and sampling

Maize grain was harvested at the end of each season in both the long and short rains. The four innermost lines in each plot were harvested.

The fresh cobs were counted, weighed and recorded. Eight cobs were selected per plot, from the shortest to the longest. These were air dried at University of Eldoret greenhouse after which they were shelled. The shelled grains were weighed and recorded. After which the following calculations were extrapolated to give grain yield in t ha^{-1}.

$$Dry\ grain\ weight\ per\ plot = \frac{Total\ Cobs\ Fresh\ weight}{Sample\ Cobs\ Fresh\ weight} * Shelled\ grains\ weight$$

$$Dry\ grain\ weight\ per\ sample\ (kg) = \frac{10000m^2}{9m^2} * Dry\ grain\ weight\ per\ plot$$

$$Dry\ grain\ weight\ per\ ha\ (t) = \frac{Dry\ grain\ weight\ per\ sample}{1000kg}$$

3.9 Data Analysis

Correlation analysis were done using Microsoft Excel version 2016 to identify the relationship among selected soil parameters for each site sites. These parameters included texture, aggregate stability, field capacity and permanent wilting point.

The model used for analysis was this:

$$\gamma = \mu + R_i + T_j + D_k + S_l + RT_{m(ij)} + RD_{n(ik)} + RS_{p(il)} + TD_{q(jk)} + TS_{r(jl)} + DS_{s(kl)} + RTD_{t(ijk)} + RTS_{u(ijl)} + RDS_{v(ikl)} + TDS_{w(jkl)} + RTDS_{x(ijkl)} + \varepsilon_{y(ijkl)}$$

Key:

μ is the overall mean

R_i is the i^{th} observation as a result of Regions

T_j is the j^{th} observation as a result of Fertilizer Treatments

D_k is the k^{th} observation as a result of Depths

S_l is the l^{th} observation as a result of Seasons

$RT_{m(ij)}$ is the mth observation as a result of interaction of Regions and Fertilizer treatments

$RD_{n(ik)}$ is the nth observation as a result of interaction of Regions and Depths

$RS_{p(il)}$ is the pth observation as a result of interaction of Regions and Seasons

$TD_{q(jk)}$ is the qth observation as a result of interaction of Fertilizer treatments and Depths

$TS_{r(jl)}$ is the rth observation as a result of interaction of Fertilizer treatments and Seasons

$DS_{s(kl)}$ is the sth observation as a result of interaction of Depths and Seasons

$RTD_{t(ijk)}$ is the tth observation as a result of interaction of Regions, Fertilizer treatments and Depths

$RTS_{u(ijl)}$ is the uth observation as a result of interaction of Regions, Fertilizer treatments and Seasons

$RDS_{v(ikl)}$ is the vth observation as a result of interaction of Regions, Depths and Seasons

$TDS_{w(jkl)}$ is the wth observation as a result of interaction of Fertilizer treatments, Depths and Seasons

$RTDS_{x(ijkl)}$ is the xth observation as a result of interaction of Regions, Fertilizer treatments, Depths and Seasons

$\varepsilon_{y(ijkl)}$ is the yth observation as a result of experimental error

Analyses of variance was done using JMP (statistical software) version 14. The nature of the experiment was RCBD. The factors included two regions (Busia-north and Bungoma-southwest), two depths (deep and shallow sites), three fertilizer treatments (one - absolute control, two – a combination of organic and inorganic fertilizers and three – pure inorganic fertilizers) and two cropping seasons (LR and SR 2015); as per the model above.

A mixed model approach was used to process the generated data, due to the multi-environmental nature of the experiments. Multi-environment trials produce results which are significantly confident where a high magnitude of environmental effects and interactions with treatments can be learned. Fixed factors in this experiment were the regions, seasons, soil depth and treatments. The random factors were farmers’ fields and replicates. Statistical significance a level of $P \leq 0.05$ was inferred to show the effects fixed factors and their interactions.

CHAPTER FOUR

RESULTS

4.1 Initial soil characteristics

Analyses conducted on initial physicochemical characteristics of the soils are shown in Table 4. All the fields had higher sand content compared to the other soil particles. The textural classes of five out of the eight field were loamy sand with 75% sand, two were sandy loam (69% sand) and one was sand (86% sand). The experimental fields had a high variability in aggregate stability with ranges between 27 to 91%. Water availability at FC and PWP also differed across the fields with BUN01 having the smallest field capacity (26.6%) and BUN03 the largest (36.33%). As expected, BUS01 with the highest sand content had the least PWP (0.9%). Bulk density exceeded the optimum range of 1.5 g cm^{-3} for all the fields except BUS03 and BUS02 at 1.41 g cm^{-3} and 1.31 g cm^{-3}, respectively.

The soil pH ranged between strongly acidic to moderately acidic. Total Nitrogen was low at all the experimental sites (< 0.12%). Available P levels were also low in all the sites (< 10 mg kg^{-1}) except for BUN02 which had a moderate amount (13.76 mg kg^{-1}). Organic Carbon levels fell below fertility threshold of 2% for all the sites while the exchangeable cations were low (< 10 cmol kg^{-1}) in all the fields with BUS02 having 0 amount. The variation of soil classes of the experimental fields gave a further understanding to their characteristics.

Table 4: Physicochemical characteristics of the study soils at the onset of the experiments

SOIL CHARACTERISTICS	SITE	BUS01	BUS02	BUS03	BUS04	BUN01	BUN02	BUN03	BUN04
PHYSICAL	**SAND (%)**	86	75	79	83	70	69	69	83
	SILT (%)	9	6	10	11	24	21	9	6
	CLAY (%)	5	18	11	6	6	10	22	11
	Textural Class	Sand	Loamy Sand	Loamy Sand	Loamy Sand	Loamy Sand	Sandy Loam	Sandy Loam	Loamy Sand
	SA	63	27	44	53	91	84	68	54
	FC (%)	29.70	33.17	36.13	26.93	26.63	34.70	36.33	30.83
	PWP (%)	0.90	1.27	1.22	1.85	1.52	1.15	1.77	1.12
	BD (g cm^{-3})	1.62	1.41	1.31	1.55	1.50	1.54	1.52	1.77
CHEMICAL	**pH**	5.9	5.63	5.95	5.84	5.57	5.58	5.15	5.35
	N_Total (%)	0.027	0.057	0.045	0.027	0.101	0.085	0.091	0.051
	P_Avail (mg kg^{-1})	5.88	4.5	4.65	7.92	8.82	13.76	5.58	5.47
	C_Org (%)	0.32	0.69	0.64	0.37	1.26	1.01	1.18	0.57
	CEC (cmol kg^{-1})	3	0	9	5	4	5	3	4
CLASSIFICATION		Gleyic Arenosols	Plinthic Arenosols	Plinthic Acrisols	Plinthic Acrisols	Stagnic Luvisols	Plinthic Acrisols	Ferric Alisols	Eutric Cambisols

This is a brief summary of various physical and chemical characteristics of the study sites and their soil types.
Key: The acronyms stated above denote: SA - stable aggregates, F.C. -Field capacity, P.W.P. – Permanent wilting point, BD – Bulk density, N_Total – Total Nitrogen, P_Avail – Available Phosphorus, C_Org – Organic Carbon and C.E.C. – cation exchange capacity.
Classification according to WRB (2006)

4.2 Relationship among soil physical characteristics in P.R.S.

Several attributes showed strong relationships due to high correlation (r > 0.5) as seen in Table 5. The strongest relationship observed was that of water content between FC and PAW with the highest value (r>0.99). An increase in FC led to higher PAW. The second highest correlation was that of silt and stable aggregates (r>0.84); where higher silt amount had larger amounts of stable aggregates. Field capacity and clay particles had a strong positive influence on each other (r>0.71); where higher clay amount, increased water held at FC. His was similar as for high clay content also increased PAW (r>0.68). Lastly, a negative but high correlation observed was that of sand and silt at -0.59; where if sand amount was high, silt was low.

Table 5: Correlation of selected soil physical parameters analyzed at the onset of the study

	Sand	**Silt**	**Clay**	**Stable Aggregates**	**Field Capacity**	**PWP**	**PAW**
Sand	1						
Silt	**-0.5873**	1					
Clay	-0.4774	-0.4309	1				
Stable Aggregates	-0.4829	**0.8398**	-0.3733	1			
Field Capacity	-0.3779	-0.2692	**0.7136**	-0.2392	1		
PWP	-0.3391	0.1239	0.2435	0.1048	-0.1656	1	
PAW	-0.3425	-0.2750	**0.6803**	-0.2434	**0.9965**	-0.2472	1

This is a summary of relationship between various soil physical characteristics measured. In this table, the initials PWP denotes Permanent wilting point and PAW stands for Plant available water. The highlighted figures indicate strong correlation between the relevant parameters.

4.3 Water infiltration rate in PRS

Water infiltration rate as referred to Table 6, was not affected by region irrespective of soil depth and fertilizer use. Farmers' fields considered to have adequate rooting depth (> 20 cm) had a larger infiltration rate (12.97 cm hr^{-1}) compared to those with a shallow rooting depth (9.26 cm hr^{-1}). Application of different types of fertilizers affected water infiltration. The highest infiltration rate (11.90 cm hr^{-1}) was observed when fertilizer was applied from both inorganic and organic sources. Application of pure inorganic fertilizer treatment had the least at 10.35 cm hr^{-1} while the control had at 11.11 cm hr^{-1}. Short rain (SR) season had the highest observed infiltration rate (12.58 cm hr^{-1}) while that of LR season was 9.66 cm hr^{-1}. Therefore, the rate of infiltration differed significantly for both fertilizer treatment and season ($P < 0.001$).

The interactions of the region and fertilizer treatment and that of region and season affected the rate of infiltration ($P < 0.05$ and $P < 0.01$ respectively). It is observed that regardless of the fertilizer treatments, Busia region had the highest infiltration in absolute control (13.79 cm hr^{-1}), combined organic and inorganic fertilizers (13.74cm hr^{-1}) and pure inorganic fertilizer (12.58 cm hr^{-1}) and, respectively. Only Bungoma region with combined organic and inorganic fertilizers application had a mean that was similar to that of Busia (in all fertilizer treatments) at 10.06 cm hr^{-1}. Absolute control and pure inorganic fertilizer in Bungoma, had the least observed infiltration rate of 8.42 and 8.12 cm hr^{-1} respectively. The interactions of fertilizer treatment and depth and that of fertilizer treatment and season displayed a large influence on infiltration rate ($P <0.0001$, $P < 0.01$ respectively). In addition, 3 tiers interactions of region, fertilizer treatment and depth; and region, depth and season did influence the infiltration rate ($P < 0.0001$ and $P < 0.05$ respectively

Table 6: Infiltration rate (cm hr^{-1}) in PRS in Bungoma and Busia regions, with three fertilizer treatments during long and short rain seasons of 2015 in deep and shallow farmers' fields

	Busia							**Bungoma**											
	LR			**SR**				**LR**			**SR**								
	Deep	**Shallow**	**Avg Bus LR**	**Deep**	**Shallow**	**Avg Bus SR**	**Avg Bus**	**Deep**	**Shallow**	**Avg Bun LR**	**Deep**	**Shallow**	**Avg Bun SR**	**Avg Bun**	**AVG F.T.**	**AVG LR**	**AVG SR**	**AVG Deep**	**AVG Shallow**
F.T.1	11.46	13.16	12.31	17.26	13.27	15.26	13.79	13.14	3.31	8.22	13.28	3.98	8.63	8.42	**11.11**	**10.27**	**11.94**	**13.78**	**8.43**
F.T.2	13.48	9.79	11.63	17.54	14.17	15.85	13.74	8.65	7.98	8.31	11.40	12.20	11.80	10.06	**11.90**	**9.97**	**13.83**	**12.77**	**11.03**
F.T.3	11.79	8.71	10.25	16.83	12.98	14.91	12.58	10.03	4.39	7.21	10.85	7.23	9.04	8.12	**10.35**	**8.73**	**11.97**	**12.37**	**8.33**
Mean (D)	12.24	10.55		17.21	13.47			10.60	5.23		11.84	7.80							
Mean (S)			11.40			15.34				7.91			9.82						
Mean (R)							13.37							8.87					
Total Mean																**9.66**	**12.58**	**12.97**	**9.26**
S.E.D R	3.7823																		
S.E.D T	0.3629***																		
S.E.D D	3.7823																		
S.E.D S	0.2963***																		
S.E.D R*T	3.8054*																		
S.E.D R*D	5.349																		
S.E.D R*S	3.7939**																		
S.E.D T*D	3.8054***																		
S.E.D T*S	0.5133**																		
S.E.D D*S	3.7939																		
S.E.D R*T*D	5.3817***																		
S.E.D R*D*S	5.3653*																		
S.E.D T*D*S	3.8399																		
S.E.D R*T*S	5.0761																		
S.E.D R*T*D*S	5.4304																		

Key: R – Region, LR – Long rain, SR – Short rain, F.T. /T.– Fertilizer treatment, D – Depth, Avg – Average and S.E.D. – standard error of the means difference. × is used to show interactions of the factors according to their stated keywords while * expresses level of significance; * = $P < 0.05$, ** = $P < 0.01$ and *** = $P < 0.001$.

4.4 Penetration resistance in poorly responsive soils

4.4.1 Penetration resistance at 10 cm

Overall, penetration resistance at a depth of 10 cm as observed on Table 7 was below 0.4 MPa. Busia-north region had the highest observation of 0.37 MPa which was not of contrast to that of Bungoma-southwest (0.33 MPa). The influence of fertilizer treatments was not distinct with absolute control having a value of 0.36 MPa, combination of organic and inorganic fertilizers at 0.35 MPa and pure inorganic fertilizer at 0.34 MPa. The dissimilarity in depths of the sites exhibited higher penetration resistance in the shallow areas (0.36 MPa) compared to the deep (0.33 MPa). It is therefore justified to point out that region, depth and fertilizer treatment did not have any noticeable effect on penetration resistance observed at 10 cm depth. However, SR season had a distinctively high penetration resistance in comparison with LR (0.39 MPa and 0.30 MPa, respectively at $P < 0.0001$).

It was observed for this parameter that only the interaction of region and season influenced penetration resistance ($P < 0.001$). Busia-north at SR season had the highest observed penetration resistance (0.39 MPa) followed by Bungoma-southwest at the same season (0.39 MPa) with these means contrast being inconsequential. Busia-north at LR season (0.34 MPa) gave similar results as Bungoma-southwest at the same season 0.27 MPa. This points out to that the season is the main factor that influenced penetration resistance at 10 cm.

Table 7: Penetration resistance (MPa) at 10 cm in PRS in Bungoma and Busia regions, with three fertilizer treatments during long and short rain seasons of 2015 in deep and shallow farmers' fields

	Busia							Bungoma											
	LR			**SR**				**LR**			**SR**								
	Deep	**Shallow**	**Avg Bus LR**	**Deep**	**Shallow**	**Avg Bus SR**	**Avg Bus**	**Deep**	**Shallow**	**Avg Bun LR**	**Deep**	**Shallow**	**Avg Bun SR**	**Avg Bun**	**AVG F.T.**	**AVG LR**	**AVG SR**	**AVG Deep**	**AVG Shallow**
F.T.1	0.33	0.32	0.32	0.46	0.40	0.43	0.38	0.25	0.31	0.28	0.42	0.41	0.41	0.35	0.36	0.30	0.42	0.36	0.36
F.T.2	0.30	0.38	0.34	0.37	0.37	0.37	0.35	0.29	0.28	0.29	0.37	0.41	0.39	0.34	0.35	0.31	0.38	0.33	0.36
F.T.3	0.35	0.35	0.35	0.35	0.41	0.38	0.36	0.20	0.30	0.25	0.35	0.39	0.37	0.31	0.34	0.30	0.37	0.31	0.36
Mean (D)	0.33	0.35		0.39	0.39			0.24	0.30		0.38	0.40							
Mean (S)			0.34			0.39				0.27			0.39						
Mean (R)							0.37							0.33					
Total Mean																0.30	0.39	0.33	0.36
S.E.D R	0.04287																		
S.E.D T	0.01416																		
S.E.D D	0.04287																		
S.E.D S	0.01156***																		
S.E.D R*T	0.04588																		
S.E.D R*D	0.06063																		
S.E.D R*S	0.0444**																		
S.E.D T*D	0.04588																		
S.E.D T*S	0.02002																		
S.E.D D*S	0.0444																		
S.E.D R*T*D	0.06489																		
S.E.D R*D*S	0.06279																		
S.E.D T*D*S	0.05006																		
S.E.D R*T*S	0.05006																		
S.E.D R*T*D*S	0.0708																		

Key: R – Region, LR – Long rain, SR – Short rain, F.T. /T.– Fertilizer treatment, D – Depth, Avg – Average and S.E.D. – standard error of the means difference. × is used to show interactions of the factors according to their stated keywords while * expresses level of significance; * = P < 0.05, ** = P < 0.01 and *** = P < 0.001.

4.4.2 Penetration Resistance at 20 cm

Region, fertilizer treatment and season did not independently spur penetration resistance at 20 cm (Table 8) as observed in this study. However, depth explicitly influenced this parameter ($P < 0.05$). The sites with inadequate rooting depths (shallow) had a conspicuous value of 5.30 MPa compared to those with sufficient (> 20 cm) (0.86 MPa). Noteworthy, three out of the four shallow sites having the maximum penetration resistance reading of 6.89 MPa.

Pairwise interactions of region and fertilizer treatment; fertilizer treatment and season significantly influenced penetration resistance at this depth of 20 cm ($P < 0.01$ and $P < 0.001$ respectively). However, their means were similar. Three tier interactions of region, fertilizer treatment and depth; region, fertilizer treatment and season; and fertilizer treatment, depth and season had significant influence on penetration resistance at (P values of < 0.001, < 0.0001 and < 0.001 respectively). In addition, the interaction of all the main effects, region, fertilizer treatment, depth and season also gave a footprint of all the factors combined being of influence to this parameter ($P < 0.0001$).

Table 8: Penetration resistance (MPa) at 20 cm in PRS in Bungoma and Busia regions, with three fertilizer treatments during long and short rain seasons of 2015 in deep and shallow farmers' fields

	Busia							Bungoma											
	LR			SR				LR			SR								
	Deep	Shallow	Avg Bus LR	Deep	Shallow	Avg Bus SR	Avg Bus	Deep	Shallow	Avg Bun LRS	Deep	Shallow	Avg Bun SR	Avg Bun	AVG F.T.	AVG LR	AVG SR	AVG Deep	AVG Shallow
F.T.1	1.19	6.89	4.04	0.85	6.89	3.87	3.95	0.76	3.71	2.23	0.74	3.72	2.23	2.23	3.09	3.14	3.05	0.88	5.30
F.T.2	0.70	6.89	3.80	0.93	6.89	3.91	3.85	0.96	3.72	2.34	0.76	3.73	2.25	2.29	3.07	3.07	3.08	0.84	5.31
F.T.3	0.81	6.89	3.85	1.01	6.89	3.95	3.90	0.81	3.71	2.26	0.81	3.70	2.25	2.26	3.08	3.05	3.10	0.86	5.29
Mean (D)	0.90	6.89		0.93	6.89			0.84	3.71		0.77	3.72							
Mean (S)			3.89			3.91				2.28			2.24						
Mean (R)							3.90							2.26					
Total Mean																3.09	3.08	0.86	5.30
S.E.D R	1.5869																		
S.E.D T	0.02117																		
S.E.D D	1.5869*																		
S.E.D S	0.01729																		
S.E.D R*T	1.5857**																		
S.E.D R*D	2.2442																		
S.E.D R*S	1.587																		
S.E.D T*D	1.5871																		
S.E.D T*S	0.02994**																		
S.E.D D*S	1.587																		
S.E.D R*T*D	2.2444**																		
S.E.D R*D*S	2.2444																		
S.E.D T*D*S	1.58738**																		
S.E.D R*T*S	1.58738***																		
S.E.D R*T*D*S	2.2449***																		

Key: R – Region, LR – Long rain, SR – Short rain, F.T. /T.– Fertilizer treatment, D – Depth, Avg – Average and S.E.D. – standard error of the means difference. × is used to show interactions of the factors according to their stated keywords while * expresses level of significance; * = $P < 0.05$, ** = $P < 0.01$ and *** = $P < 0.001$.

4.4.3 Penetration Resistance at 30 cm

Penetration resistance at 30 cm was highest compared to that of previous depths (PR at 10 and 20 cm) as observed on Table 9. Irrespective of region, penetration resistance at 30 cm was affected by depth, fertilizer treatment and season ($P < 0.05$, < 0.05 and < 0.0001 respectively). At this depth, the four fields with inadequate rooting depth (shallow) had an elevated penetration resistance reading (6.89 MPa) compared to that of deep ones (2.83 MPa). Interestingly, fertilizer treatment 3 (pure inorganic) had a distinctive high measurement (4.91 MPa), compared to those of absolute control (4.82 MPa) and combination of organic and inorganic fertilizers (4.86 MPa). The influence of seasons was significant as SR recorded the highest measurement at 4.87 MPa noticeably contrasting LR at 4.85 MPa.

Pairwise interactions of region and season; fertilizer treatment and depth, fertilizer treatment and season; and depth and season influenced penetration resistance recorded at 30 cm ($P < 0.05$, <0.05, 0.001 and < 0.0001 respectively). Worthy of attention is that Busia-north at both seasons recorded the highest penetration resistance at 30 cm (5.51 and 5.53 MPa for LR and SR respectively) while Bungoma-southwest had the least (SR 4.21 and LR 4.19 MPa). Shallow fields had the overall highest penetration resistance (6.89 MPa) regardless of the fertilizer treatment. This was however noticeably different from deep fields with pure inorganic fertilizers applied had a moderate recording at 2.93 MPa, and deep fields with combination of inorganic and organic had the least penetration resistance.

The 3 tiers interactions with consequential influence on this parameter were region, fertilizer treatment and season ($P < 0.05$); region, depth and season ($P < 0.05$); fertilizer treatment, depth and season ($P < 0.001$). In addition, the interaction of all the main effects; region, fertilizer treatment, depth and season significantly influenced the outcome of the aforementioned parameter ($P < 0.05$).

Table 9: Penetration resistance (MPa) at 30 cm in PRS in Bungoma and Busia regions, with three fertilizer treatments during long and short rain seasons of 2015 in deep and shallow farmers' fields

	Busia							**Bungoma**											
	LR			**SR**				**LR**			**SR**								
	Deep	**Shallow**	**Avg Bus LR**	**Deep**	**Shallow**	**Avg Bus SR**	**Avg Bus**	**Deep**	**Shallow**	**Avg Bun LR**	**Deep**	**Shallow**	**Avg Bun SR**	**Avg Bun**	**AVG F.T.**	**AVG LR**	**AVG SR**	**AVG Deep**	**AVG Shallow**
F.T.1	3.96	6.89	5.42	3.99	6.89	5.44	5.43	1.47	6.89	4.18	1.56	6.89	4.22	4.20	4.82	4.80	4.83	2.74	6.89
F.T.2	4.15	6.89	5.52	4.27	6.89	5.58	5.55	1.39	6.89	4.14	1.52	6.89	4.20	4.17	4.86	4.83	4.89	2.83	6.89
F.T.3	4.27	6.89	5.58	4.29	6.89	5.59	5.58	1.61	6.89	4.25	1.55	6.89	4.22	4.23	4.91	4.91	4.90	2.93	6.89
Mean (D)	4.13	6.89		4.18	6.89			1.49	6.89		1.54	6.89							
Mean (S)			5.51			5.53				4.19			4.21						
Mean (R)							5.52							4.20					
Total Mean																4.85	4.87	2.83	6.89
S.E.D R	1.3339																		
S.E.D T	0.01765*																		
S.E.D D	1.3339*																		
S.E.D S	0.01441***																		
S.E.D R*T	1.334																		
S.E.D R*D	1.8864																		
S.E.D R*S	1.334*																		
S.E.D T*D	1.334*																		
S.E.D T*S	0.02496***																		
S.E.D D*S	1.334***																		
S.E.D R*T*D	1.8866																		
S.E.D R*D*S	1.8865*																		
S.E.D T*D*S	1.3343***																		
S.E.D R*T*S	1.3343*																		
S.E.D R*T*D*S	1.887*																		

Key: R – Region, LR – Long rain, SR – Short rain, F.T. /T.– Fertilizer treatment, D – Depth, Avg – Average and S.E.D. – standard error of the means difference. × is used to show interactions of the factors according to their stated keywords while * expresses level of significance; * = $P < 0.05$, ** = $P < 0.01$ and *** = $P < 0.001$.

4.5 Maize grain yield in poorly responsive soils

The fertilizer treatment and season played a crucial role with regard to the maize grain yield obtained, despite region of study and depth of the sites ($P < 0.0001$) as observed in Table 10. Application of pure inorganic fertilizer had the highest maize yield attained of 3.47 t ha^{-1} which was similar to that of combination of organic and inorganic at 3.46 t ha^{-1}. As expected, the absolute control had the least observed yield of 1.45 t ha^{-1} which was in contrast from the latter. Long rains (LR) season stood out with a higher yield than SR of 3.45 t ha^{-1} and 2.13 t ha^{-1} respectively.

Further, pairwise interactions of region and fertilizer treatment; fertilizer treatment and season; and depth and season demonstrated significant influence on maize grain yield in this study ($P < 0.001$, < 0.05 and < 0.01 respectively). Busia-north with combined application of organic and inorganic fertilizers during LR had the overall highest grain yield of 5.62 t ha^{-1}. This treatment also had the highest yield of 4.33 t ha^{-1} in LR season. This was followed by fertilizer treatment 3 in the same season (LR) with 4.17 t ha^{-1}. During the SR season, pure inorganic fertilizer application (2.77 t ha^{-1}) had a higher yield than that of combined organic and inorganic in the (2.60 t ha^{-1}). Deep rooted sites had the overall highest grain yield (2.82 t ha^{-1}) while shallow sites had a moderate yield of 2.76 t ha^{-1}. Three level interactions that influenced maize grain yield noticeably were region, fertilizer treatment and season and region, depth and season at ($P < 0.05$ and < 0.001 respectively)

Table 10: Maize grain yield (t ha^{-1}) in PRS in Bungoma and Busia regions, with three fertilizer treatments during long and short rain seasons of 2015 in deep and shallow farmers' fields

	Busia							**Bungoma**											
	LR			**SR**				**LR**			**SR**								
	Deep	**Shallow**	**Avg Bus LR**	**Deep**	**Shallow**	**Avg Bus SR**	**Avg Bus**	**Deep**	**Shallow**	**Avg Bun LRS**	**Deep**	**Shallow**	**Avg Bun SR**	**Avg Bun**	**AVG F.T.**	**AVG LR**	**AVG SR**	**AVG Deep**	**AVG Shallow**
F.T.1	3.17	1.18	2.17	1.53	0.90	1.21	1.69	1.32	1.78	1.55	0.74	0.95	0.85	1.20	1.45	1.86	1.03	1.69	1.20
F.T.2	5.62	3.86	4.74	1.99	2.63	2.31	3.52	3.65	4.18	3.91	2.67	3.10	2.89	3.40	3.46	4.33	2.60	3.48	3.44
F.T.3	3.69	3.82	3.75	2.25	2.35	2.30	3.03	4.65	4.52	4.59	2.61	3.87	3.24	3.91	3.47	4.17	2.77	3.30	3.64
Mean (D)	4.16	2.95		1.92	1.96			3.21	3.49		2.01	2.64							
Mean (S)			3.55			1.94				3.35			2.32						
Mean (R)							2.75							2.84					
Total Mean																3.45	2.13	2.82	2.76
S.E.D R	0.1966																		
S.E.D T	0.18126***																		
S.E.D D	0.4224																		
S.E.D S	0.1405***																		
S.E.D R*T	0.4652**																		
S.E.D R*D	0.2837																		
S.E.D R*S	0.2417																		
S.E.D T*D	0.4652																		
S.E.D T*S	0.2499*																		
S.E.D D*S	0.4451**																		
S.E.D R*T*D	0.658																		
S.E.D R*D*S	0.5037																		
S.E.D T*D*S	0.5251																		
S.E.D R*T*S	0.5251*																		
S.E.D R*T*D*S	0.7425**																		

Key: R – Region, LR – Long rain, SR – Short rain, F.T. /T.– Fertilizer treatment, D – Depth, Avg – Average and S.E.D. – standard error of the means difference. × is used to show interactions of the factors according to their stated keywords while * expresses level of significance; * = $P < 0.05$, ** = $P < 0.01$ and *** = $P < 0.001$.

CHAPTER FIVE

DISCUSSION

5.1 The underlying physical characteristics of poorly responsive soils and how they influence one another

The texture in the two regions across all the experimental sites was predominantly sand (> 50%). Sand content strongly influenced the amount of silt, although negatively. This is to be expected as the texture is computed on basis of the three particles; sand, silt and clay. Clay amount in the soils was the least. The texture is a fixed property which affects all the other soil properties; its influence is largely felt by land use capability and soil management (Phogat, Tomar, & Dahiya, 2015).

The highest stable aggregates measured was in BUN01 at 91% while BUS02 had the least at 27%. The field BUN01 is a stagnic Luvisol, and the clay in this site had eluviated from topsoil to subsurface. BUN02 had 84% stable aggregates; being a plinthic Acrisol, the site has low activity clay. These two fields had the highest stability of aggregates which is associated with their soil types. The site BUS02 is a plinthic Arenosol that exhibits high sand content, low clay content and low SOM. The organic Carbon in this site is 0.69% while clay is 18%.

This parameter pinpoints the ability of a soil to resist mechanical stress experienced in high rainfall and runoff, thus directly influencing erodibility (Siddique, Sultana, & Abdullah, 2017). An increase in erodibility leads to a decrease in aggregate stability.

Low aggregate stability such as in BUS02 (27%), BUS03 (44%) and BUS04 (53%) indicate a breakdown of soil particles that cause blocking of soil pores that reduce hydraulic conductivity (Lal & Shukla, 2004). This is a form of degradation at the surface and sub-soil layers that reduce water use efficiency mostly experienced in arid and semi-arid regions (CIMMYT, 2013) which is consensual with this study of PRS in Western Kenya. This parameter has also been reported to influence solute transport processes and resistance of roots to penetration (Díaz-Zorita, Perfect, & Grove, 2002) , which hindered plant growth and yield in PRS. Intensive agricultural practice is the second factor that leads to the deterioration of aggregate stability due to a decline in organic matter content (Annabi *et al.,* 2014).

The stability of aggregates correlated strongly with silt particles in this experiment, this is due to the low organic Carbon content and low clay in the experimental sites which hindered aggregate formation. Six *et al.,* (2000) reported that soils in tropics were deficient of organic matter and tend to rely on other materials to form aggregates. In this study, clay particles ranged between 5 – 22%; thus, silt formed the basis of forming stable aggregates. However, it was noted that mainly there was low aggregate stability in most of the farmers' fields. In a study conducted in Western Kenya, Cebula (2013) reported high variability in aggregate stability (15. 3 – 79.2%) which is similar to findings in this study. This shows that heterogeneity of soils is wide across this region as well as the influence of low versus high reactivity clays in aggregate formations. Annabi *et al.,* (2014) reported an increase in aggregate stability by up to 50% in the field, 18 months after the addition of organic amendments. Additional research of PRS is required over time to see if the increase of organic amendments improves the stable aggregates.

Water availability at field capacity had a high correlation (r = 0.71) with clay content which is in agreement with reports by Webb (2004) who reported that field capacity correlated with clay content (r = 0.73). In sandy soils with little amounts of organic matter, the clay particles are responsible for holding water in the micropores. Markoski *et al.*, (2013) also established a positive correlation of water retention to clay, silt and humus. Plant available water has a high correlation with field capacity as it is derived from the difference of field capacity and permanent wilting point.

5.2 Water infiltration rate in poorly responsive soils

Overall, the infiltration rate was within the reported range for Western Kenya region (Cebula, 2013) and the tropics (Moroke, Dikinya, & Patrick, 2009). The infiltration rate of the shallow fields was lower compared to that of deep fields. This is observed due to the fact that the shallow fields had interference on the horizon as a result of plinthite and ferric properties (see section 4.1). Plinthite creates a hardpan which is hard to weather and impermeable (WRB, 2006) thus hindering movement of water and nutrients within the profile. Sesquioxides in the ferric layer formed concretions which were packed closely and clogged soil pores and thus hindered the movement of water.

However, it was noticeably observed that BUN01 had the least rate of infiltration across all the experimental fields. This results from stagnic properties of the soils in this field which allow for water to remain standing over long periods of time (FAO, 2006). This was further aggravated by the luvic characteristics of this site where clay had eluviated from top to sub horizon. This created an impermeable layer which hindered the flow of water due to fewer macropores which are associated with clay particles (Phogat *et al.*, 2015).

The fields, BUN04 had the highest observed infiltration rate due to the good development of the soil profile as it is a Cambisol. These relatively young soils' and well drained (WRB, 2006) which influenced the high infiltration rates. The hinderance of roots by impermeable soil layers is a subsurface cause of poor response by crops as they cannot access adequate nutrients and water (Hartmann, et al., 2008).

Absolute control and pure inorganic fertilizer application had significantly lower infiltration rates than where combined organic and inorganic fertilizers had been applied. The combination of organic and inorganic fertilizers improved infiltration rates remarkably. This results from the permeability of organic materials which increases water retention even in PRS. Busari and Salako (2015) reported an increase in infiltration rate after addition of organic amendment. In addition, it served as a boost to the physical characteristics of the shallow fields which had initial hindrance by plinthic layer and ferric properties.

The two seasons in which the experiment was conducted had a higher water infiltration rate in SR than in LR. The precipitation amount during the LR is more than that experienced during the SR (Jaetzold *et al.*, 2005). Therefore, rain water during LR fills up the soil pores which resulted in a lower readings of infiltration rates compared to those of SR. This also contributed to interactions between region and season; and fertilizer treatment and season; where high infiltration rates are observed in Busia-north during SR where combined organic and inorganic fertilizers were applied.

The interaction of region and fertilizer treatment were of consequence on infiltration rate. Busia-north had the overall highest infiltration rate compared to Bungoma-southwest.

This attributes to the high sand content in Busia-north sites which promote infiltration rates (Murphy, 2014). Strong reliance on organic matter addition is observed in Bungoma where application of combined organic and inorganic fertilizers improved the infiltration rate to similar levels with sandy-textured sites in Busia-north. Another interaction which plays a significant role is fertilizer treatment and depth; this owes to shallow soils having compaction with no significant increase in infiltration rates even after application of organic amendments. Decreasing compaction in PRS is therefore necessary to improvement water infiltration and water holding capacity in shallow sites (Dexter, 2004)

It is worthy of mention that increase in infiltration rate was observed when soil fertility was improved (Dunjana *et al.*, 2014) and compaction decreased (Dexter, 2004). The influence of organic matter addition for a period of 8 years did not have any effect on infiltration rate (Cebula, 2013) in Western Kenya; this may be due to compaction at subsurface horizons. Thus, in order to rehabilitate PRS, the addition of organic matter and other practices such as deep tillage in compacted soils need to be paired in areas which face sub-soil compaction in order to improve infiltration rate.

5.3 Penetration resistance in poorly responsive soils

Penetration resistance readings at 10 cm were low (< 0.4 MPa). This was expected due to the fact that tillage of land was done using handhoes prior to planting before each season. At the time of taking the readings, the soil structure was between fine and columnar; the moisture content levels were sufficient (a week after continuous rainfall event) (Duiker, 2002). The soils had no compaction on the surface.

Tillage was reported to increase air porosity of soil up to the depth of contact (Abu-Hamdeh, 2002) as in the case of this study on PRS. Due to similar tillage practices, there were no relevant consequences of regions, fertilizer treatments and depth on penetration resistance at 10 cm.

Short rains had significantly higher penetration resistance readings than the long rains. This is attributed to the higher soil moisture content in LR than in SR. High water content leads to low penetration resistance (Nawaz *et al.,* 2013; Duiker, 2002). The interaction of region and season bore significant differences with Busia-north at SR having a high PR reading than Bungoma-south west in the same season. This owes to the high porosity of soils with high sand content which did not retain sufficient water and also low precipitation during short rains. Insufficient moisture content is reported to interfere with PR reading by increasing resistance (Duiker, 2002).

Penetration resistance readings at 20 cm were highest in the shallow than in the deep fields. All shallow fields at 20 cm (except BUN03) became too compact and impenetrable; a parameter that attribute poor response of soils to fertilizer application. These fields BUS02, BUS03 and BUN02 had a high PR due to an impenetrable hardpan created by plinthic layer. The field BUN03 is a ferric Alisol which has high clay content in the subsoil (WRB, 2006). Although the ferric layer was impenetrable by a soil auger, the penetrometer which is narrower and pinpointed was not hindered by the concretions. A penetrometer mimics the ability of roots to grow into the soil (Whalley *et al.*, 2007);

this clearly shows that the 3 sites aforementioned are too compact from 20 cm depth to support any root growth. They exceeded the critical root growth limit of 3 MPa (Sinnet *et al.*, 2008).

Interactions of a region and fertilizer treatment; fertilizer treatment and season; region, fertilizer treatment and depth; region, fertilizer treatment and season; and fertilizer treatment, depth and season influenced penetration resistance at 20 cm. Fertilizer treatment is the factor that stands out in all these interactions. This shows that the source of fertilizer used has a role to play in influencing penetration resistance in PRS, although not independently in this study. Application of combination of organic and inorganic fertilizers gave lower PR readings as organic material improved soil structure in PRS. This clearly shows that organic matter is one of the necessary means to rehabilitating PRS by reducing compaction of these soils. However, a longer period for the turnover of organic material should be allowed for any significant comparisons to be made (Murphy, 2014). However, the acquisition of sufficient amounts and good quality FYM is a challenge in Western Kenya (Titonell *et al.*, 2005). This is a challenge that could be addressed by other ways of incorporating organic materials such as retaining of crop residues or conservation agriculture (Zingore & Johnston, 2013).

Penetration resistance at 30 cm had overall the highest reading across all depths; this parameter is a clear depiction of physical constraints such as high compaction levels in sub-soil horizons in PRS. The categorically deep fields had relatively lower penetration resistance than the shallow fields. The sub-soil characteristics of the deep fields did indicate any attributes that could cause compaction; namely the gleyic, stagnic and eutric properties. However, even the deep fields had a value that indicated physical strain (2.87 MPa) in PRS; where roots struggle to obtain moisture and nutrients using old root channels (Hazelton & Murphy, 2007). This strain influences water and nutrient uptake in crops; thus, values of less than 2 MPa are required for crop growth and production.

At a depth of 30 cm, all the shallow fields were impenetrable. In the deep fields, BUS04 experienced compaction due to the plinthite layer hence the penetrometer could not move. BUN03 (ferric Alisol) also became compact at this depth. This is an indicator of subsoil constraints that interfere with plants ability to take up water and nutrients thus influence yield negatively. The role of organic matter again here is outlined in reducing compaction in PRS is again observed at this soil depth. Combined application of organic and inorganic fertilizers had the least compaction due to the organic material applied. Higher resistance is also recorded for SR due to the limited soil moisture content arising from low precipitation during this period. Subsoil compaction was reported by Nawaz *et al.,* (2013); this is associated with short periods of rainfall such as in Western Kenya and aggravated resistivity especially in sandy soils (Sakai *et al.,* 2008).

Interactions of region and season, fertilizer treatment and depth, fertilizer treatment and season, and depth and season showed strong penetration resistance for basic characteristics of PRS such as sandy dominated soils, low precipitation periods, low SOM levels and shallow tilled soils. Busia-north receives lesser precipitation (230 – 800 mm) and also has a higher rate of potential evapotranspiration (1800 – 2030 mm) compared to Bungoma-southwest which experiences rainfall of over 1000 mm and has potential evapotranspiration of 1000 – 1300 mm (Jaetzold *et al.,* 2005). This clearly outlines the effect of soil moisture on penetration resistance in PRS. Lastly, this parameter displayed influence from interaction of all the main effects; region, depth, fertilizer treatment and season. All these characteristics interfere with the growth of crop roots by inhibiting root access to lower horizons where plant nutrients and water have percolated (Siczek *et al.,* 2015) and hence would contribute to poor response to fertilizer application.

It is noted that penetration resistance increased with depth from 10 cm to 30 cm across all sites. Dependence of penetration resistance to depth and tillage method was observed by Hamza and Anderson (2005). Soil penetration resistance in PRS was higher in shallow tilled soils than in deep which is consistent with other reported observations (Jabro, Stevens, Iversen, & Evans, 2010).

In this case, all the fields were tilled using a hand hoe which goes down to a depth of 20 cm. It is, therefore, necessary to conduct further assessments on the effect of depth and tillage method on crop growth, crop development, yield, and quality (Hamza and Anderson, 2005) especially in PRS. In addition, when penetration resistance reaches the critical threshold limit of 3 MPa, root growth is impeded, water and nutrient movement restricted; this automatically affects yield of any crop (Hazelton & Murphy, 2007) as observed in PRS.

5.4 The maize grain yield in poorly responsive soils

The role of fertilizers is also well outlined in this study as the nutrients applied to maize crop had a significantly higher yield when compared to where none was applied (control).

In combined organic and inorganic; and pure inorganic fertilizers (fertilizer treatments 2 and 3), the nutrients applied (N, P, K, Ca, Cu and Zn) improved the crop growth in PRS. In the study that this research was based on, Njoroge *et al.*, (2018) reported that in order to curb the maize deficits, sole NPK applications were insufficient and addition of Ca, Zn and Cu was necessary to increase yield significantly in PRS. Kihara *et al.,* (2017) also reported increase in yield and nutrient associated to; 49.4% by S, 23.0% Zn, S and micronutrients combinations (11.5%) and less than 10% each for Cu and B.

A maize yield of increase 0.84 t ha^{-1} (25%) was reported due to S and macronutrient application compared to macronutrient only application (Kihara *et al.,* 2017). The maize grain yield was also noticeably higher in LR than SR across the regions, depths and fertilizer treatments. It is observed that the yield was 3.45 t ha^{-1} in long rains and 2.13 t ha^{-1} in short rains. This shows the important role played by moisture as it influences nutrient uptake and movement; thus, affecting yield. Balanced nutrition and sufficient water are necessary for increased crop yield. Precipitation experienced in the tropics tends to be low and unevenly distributed affecting rain-fed agriculture (Fernandes-Ugalde *et al.,* 2009) such as in PRS of Western Kenya.

Pairwise interactions gave strong reliance of each region, season and depth on fertilizer treatments applied. Deep fields held more water in LR and gave the highest yield while shallow soils performed poorly regardless of the season. This demonstrates that adequate rooting depth is necessary for crop growth and yield. Also, a very important observation is that Busia-north with combine organic and inorganic fertilizer applied had the highest yield; highlighting that the sandy textured soils require higher organic amendments to assist in boosting their physical status. While Bungoma-southwest with pure inorganic had the second highest yield showing that this particular region requires inorganic amendments primarily to tackle nutrient deficiencies. This is in agreement to Njoroge *et al.,* (2018) findings where fields in Busia responded better to application of organic and inorganic fertilizers. This shows that PRS have different needs and characteristics which are met by various means; thus, integrated approaches are required to suit for these individual needs.

However, fertilizer application solely is still not improving the yield of these particular PRS to potential yield of 6 t ha^{-1} (MOA, 2014) in Western Kenya.

This pinpoints to the fact that there is an underlying problem that is not chemical only. An underlying study carried out by Njoroge *et al.,* (2017) reported 48% of studied fields were poor responsive; characterized by low yield of maize and uneconomical benefits of fertilizer usage. Sandy textured soils were highlighted to have a low indigenous nutrients supply (Rusinamhodzi, Corbeels, Zingore, Nyamangara, & Giller, 2014) as reported in these sites with > 50% sand content. These experimental fields fell into category 4: low responsive degraded and infertile soils (Chikowo, Zingore, Snapp, & Johnston, 2014).

An array of nutrients management approaches tailored to be farm specific with a study on all soil quality parameters of PRS at a surface and sub-surface layers are required, rather than the usual blanket recommendation of fertilizers due to their poor response.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. Inherent properties; texture and aggregate stability play a role in understanding of PRS.

   Textural class of soil has the largest influence on the other soil properties (stable aggregates and water availability) as seen in all the sites. The sand content was above 50% in all the fields. The texture is a parameter felt by land use capability and soil management strategies that need to be adopted.

   Low formation of stable aggregates in PRS leads to low ability to resist mechanical stress as is in BUS02, BUS03, BUS04 and BUN04. This indicates a breakdown of soil particles that clog soil pores which in turn reduces water use efficiency, solute transport, plant accessibility to nutrients and resistance of roots to penetration. All of these pinpoints to surface and sub-soil degradation which is detrimental to crop growth.

2. Infiltration rates in PRS are affected by rooting depth. Shallow depths hinder water percolation. This results from clogging of pores due to deterioration of aggregates, eluviation of clay from top to sub-soil horizons and soil formation features such as plinthic and ferric properties. Addition of organic amendments aided water movement; and thus retention. In order to improve the infiltration rate of such afflicted soils, the addition of organic amendments is beneficial as well as deep tillage.

3. Penetration resistance increased with depth. It is also noted that penetration resistance is higher in shallow tilled than in deeply tilled soils.

   Plinthic and ferric features in sub-soil horizons also increase this parameter when the layers occur within the crop rooting zone. Water also influenced penetration resistance; during LR penetration resistance was lesser compared to SR.

4. Maize grain yield in PRS was largely affected by water and nutrients availability. Water is crucial; with deficits leading to low yield as observed in SR. As outlined in this study, balanced fertilization with both macronutrients and micronutrients (as applied in fertilizer treatments 2 and 3) is effective in increasing yield in PRS. However, target yield of 5 to 6 t ha^{-1} was still not achievable in PRS. This shows that there are still more constraints felt by PRS.

   In order to understand what influences poor responses, various parameters not withheld to regions, soil types, rooting depth, water availability and fertilizer types and how they interact with each other to influence crop growth and yield are mandatory. This is outlined in this study where sandy soils are deficient of nutrients and show more improvement in addition to inorganic fertilizers which is contrary to the expected organic and inorganic amendment approach.

6.2 Recommendations

1. Studies of soil quality (physical and chemical) on both top and sub-soil horizons are necessary to fully understand constraints of PRS; thus, allocate proper strategies to rehabilitate them.
2. The study period should be lengthened to see if the amendments applied would improve PRS.

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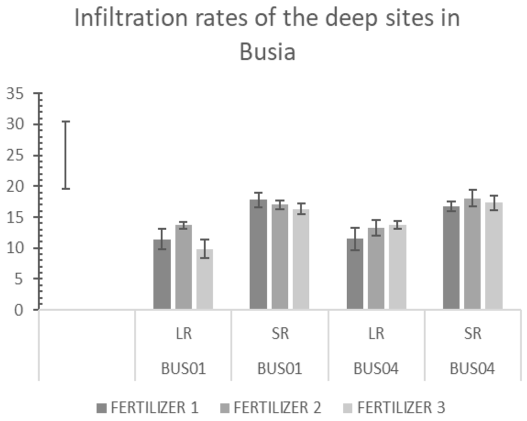
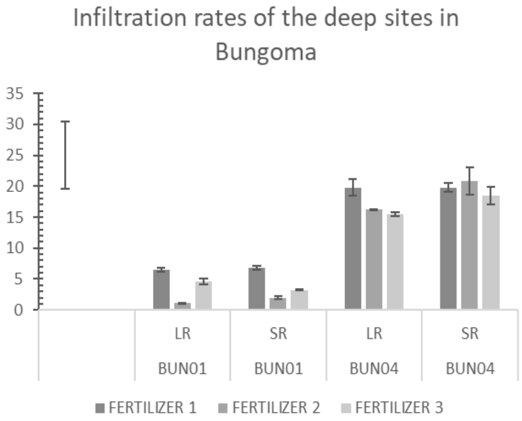
APPENDICES

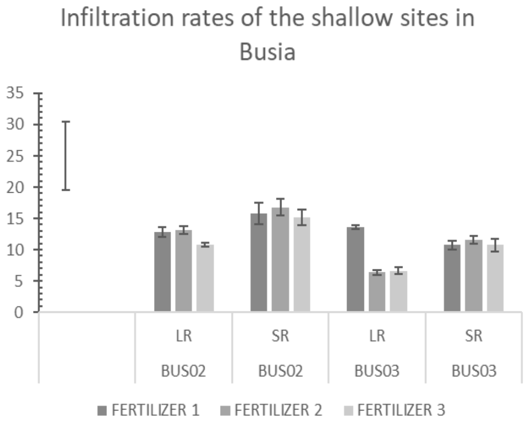
Appendix I: ANOVA table of fixed effects for infiltration rates in PRS

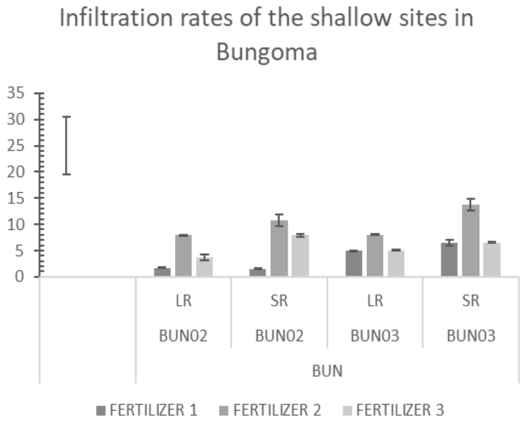
Source	Nparm	DF	DFDen	F Ratio	Prob > F
REGION	1	1	4	1.4295	0.2979
TRT	2	2	114	13.2409	<.0001*
DEPTH	1	1	4	0.9743	0.3795
SEASON	1	1	114	113.598	<.0001*
REGION*TRT	2	2	114	4.2027	0.0173*
REGION*DEPTH	1	1	4	0.0724	0.8011
REGION*SEASON	1	1	114	7.0127	0.0092*
TRT*DEPTH	2	2	114	10.7300	<.0001*
TRT*SEASON	2	2	114	6.0651	0.0031*
DEPTH*SEASON	1	1	114	1.5427	0.2168
REGION*TRT*DEPTH	2	2	114	33.0022	<.0001*
REGION*DEPTH*SEASON	1	1	114	4.8527	0.0296*
TRT*DEPTH*SEASON	2	2	114	2.1302	0.1235
REGION*TRT*DEPTH*SEASON	2	2	114	2.8034	0.0648
REGION*TRT*SEASON	2	2	114	1.5673	0.2131

Appendix II: An illustration of infiltration rate (cm hr^{-1}) in PRS







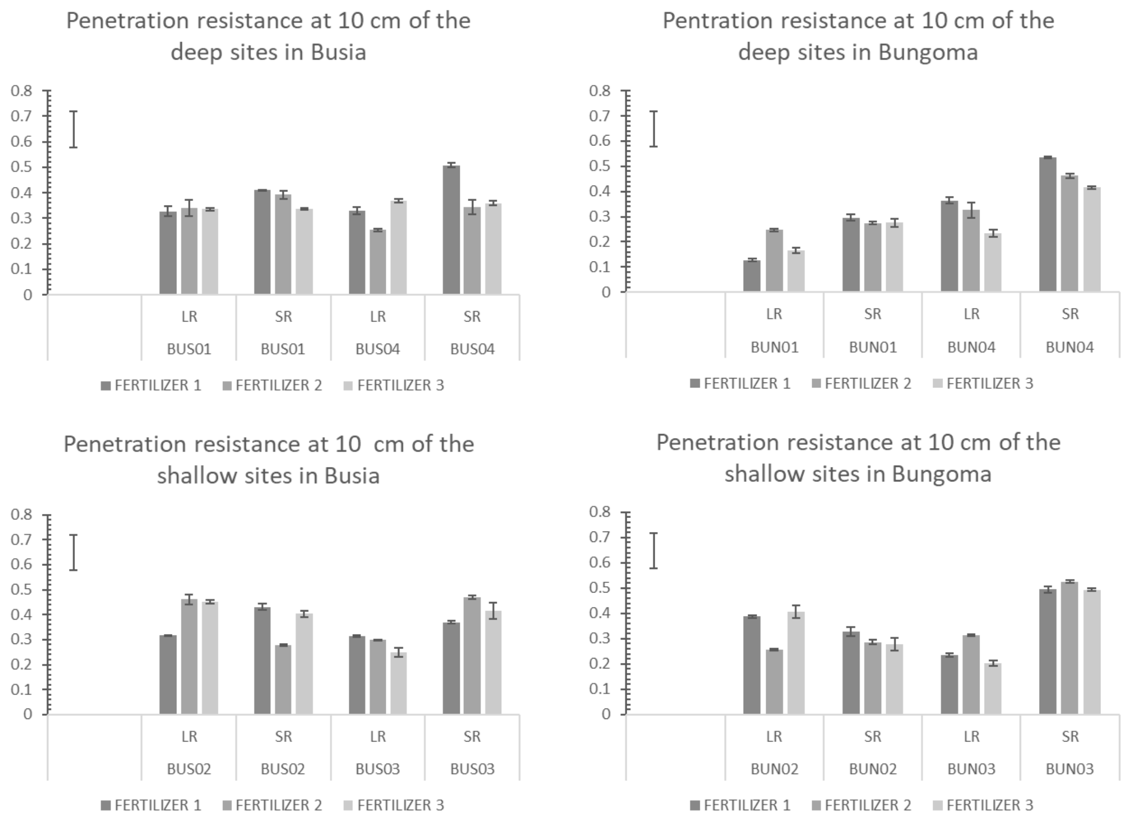


This illustrates the effect of 3 fertilizer treatments (1 - control, 2 - inorganic and organic fertilizer combination and 3 - complete inorganic fertilizer) on infiltration rates studied during long and short rains seasons of 2015; across 8 sites in Busia-north and Bungoma-southwest region. Four of these sites were shallow (< 20 cm when tilled) and the other deep (> 20 cm when tilled). The error bars are generated from standard error from each mean.

Appendix III: ANOVA Table of Fixed effects for Penetration resistance at 10 cm in PRS

Source	Nparm	DF	DFDen	F Ratio	Prob > F
REGION	1	1	4	0.6594	0.4623
TRT	2	2	114	1.5113	0.2250
DEPTH	1	1	4	0.3861	0.5680
SEASON	1	1	114	55.6123	<.0001*
REGION*TRT	2	2	114	0.8889	0.4140
REGION*DEPTH	1	1	4	0.1065	0.7606
REGION*SEASON	1	1	114	6.9672	0.0095*
TRT*DEPTH	2	2	114	1.7998	0.1700
TRT*SEASON	2	2	114	2.3080	0.1041
DEPTH*SEASON	1	1	114	1.2554	0.2649
REGION*TRT*DEPTH	2	2	114	1.4451	0.2400
REGION*TRT*SEASON	2	2	114	0.5916	0.5551
TRT*DEPTH*SEASON	2	2	114	0.5494	0.5788
REGION*TRT*DEPTH*SEASON	2	2	114	2.3719	0.0979
REGION*DEPTH*SEASON	1	1	114	0.0626	0.8028

Appendix IV: An illustration of penetration resistance at 10 cm (MPa) in PRS

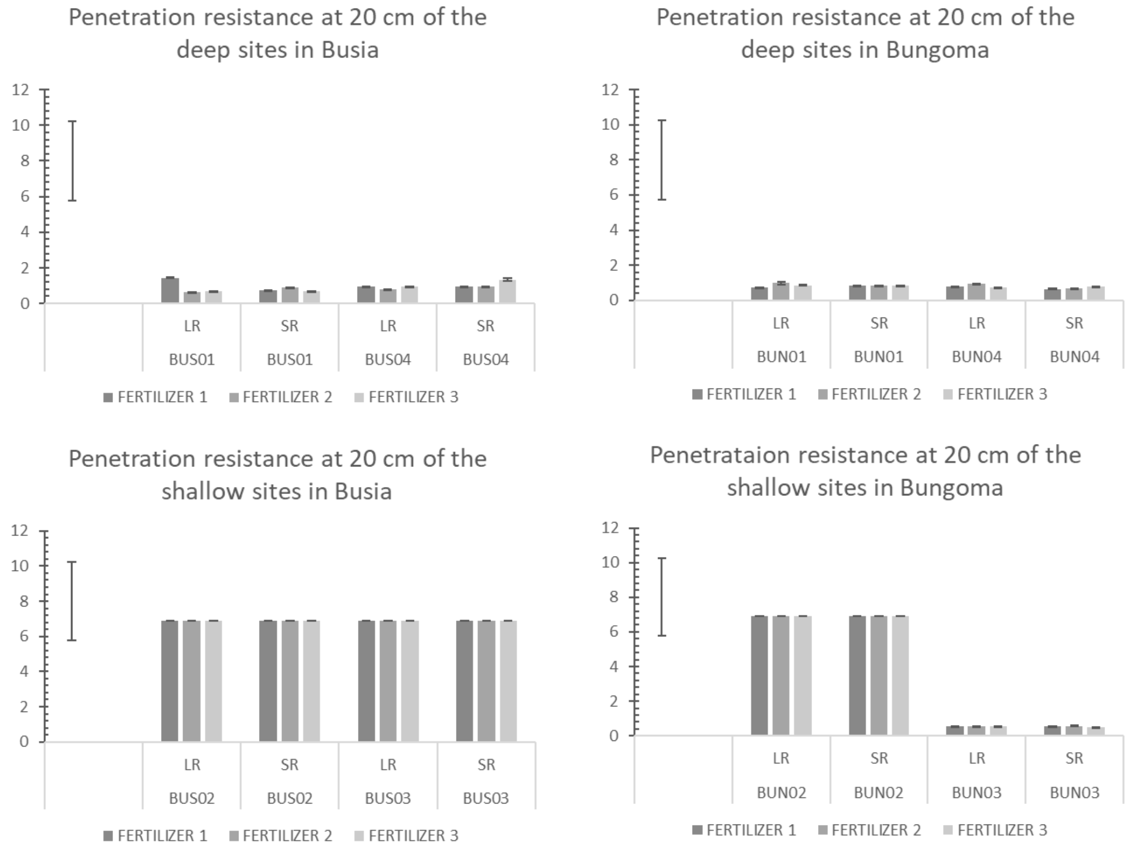


This illustrates the effect of 3 fertilizer treatments (1 - control, 2 - inorganic and organic fertilizer combination and 3 - complete inorganic fertilizer) on penetration resistance at a depth of 10 cm studied during long and short rains seasons of 2015; across 8 sites in Busia-north and Bungoma-southwest region. Four of these sites were shallow (< 20 cm when tilled) and the other deep (> 20 cm when tilled). The error bars are generated from standard error from each mean.

Appendix V: ANOVA Table of Fixed effects for Penetration resistance at 20 cm in PRS

Source	**Nparm**	**DF**	**DFDen**	**F Ratio**	**Prob > F**
REGION	1	1	4	1.0693	0.3595
TRT	2	2	114	0.5414	0.5834
DEPTH	1	1	4	7.8321	0.0489*
SEASON	1	1	114	0.3279	0.5680
REGION*TRT	2	2	114	7.1484	0.0012*
REGION*DEPTH	1	1	4	0.9318	0.3891
REGION*SEASON	1	1	114	1.7944	0.1831
TRT*DEPTH	2	2	114	0.7509	0.4742
TRT*SEASON	2	2	114	5.3185	0.0062*
DEPTH*SEASON	1	1	114	0.4563	0.5007
REGION*TRT*DEPTH	2	2	114	6.4768	0.0022*
REGION*TRT*SEASON	2	2	114	10.2825	<.0001*
REGION*DEPTH*SEASON	1	1	114	2.0805	0.1519
TRT*DEPTH*SEASON	2	2	114	6.0306	0.0032*
REGION*TRT*DEPTH*SEASON	2	2	114	10.1243	<.0001*

Appendix VI: An illustration of penetration resistance at 20 cm (MPa) in PRS

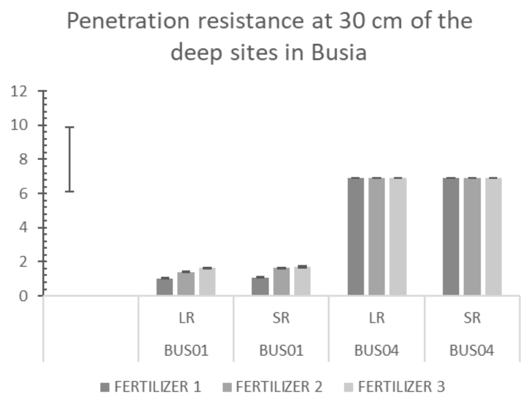


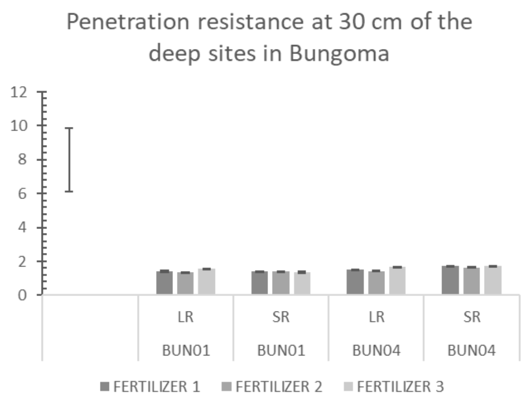
This illustrates the effect of 3 fertilizer treatments (1 - control, 2 - inorganic and organic fertilizer combination and 3 - complete inorganic fertilizer) on penetration resistance at a depth of 20 cm studied during long and short rains seasons of 2015; across 8 sites in Busia-north and Bungoma-southwest region. Four of these sites were shallow (< 20 cm when tilled) and the other deep (> 20 cm when tilled). The error bars are generated from standard error from each mean.

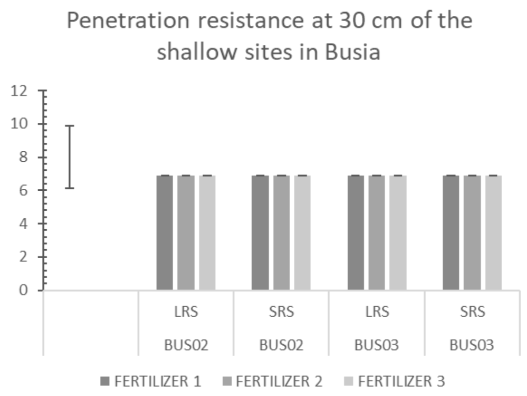
Appendix VI: ANOVA Table of Fixed effects for Penetration resistance at 30 cm in PRS

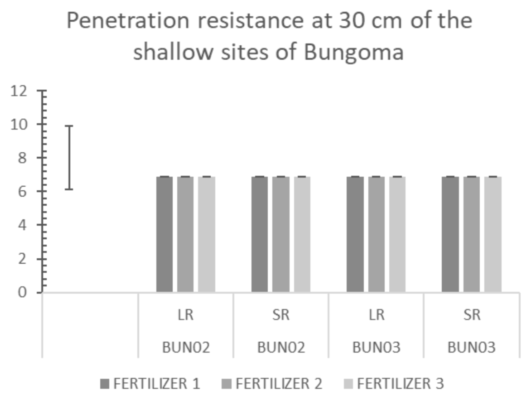
Source	Nparm	DF	DFDen	F Ratio	Prob > F
REGION	1	1	4	1.0306	0.3674
TRT	2	2	114	4.5944	0.0121*
DEPTH	1	1	4	9.0824	0.0394*
SEASON	1	1	114	17.3579	<.0001*
REGION*TRT	2	2	114	0.8334	0.4372
REGION*DEPTH	1	1	4	1.0306	0.3674
REGION*SEASON	1	1	114	5.8160	0.0175*
TRT*DEPTH	2	2	114	4.5944	0.0121*
TRT*SEASON	2	2	114	8.2527	0.0004*
DEPTH*SEASON	1	1	114	17.3579	<.0001*
REGION*TRT*DEPTH	2	2	114	0.8334	0.4372
REGION*TRT*SEASON	2	2	114	3.4446	0.0353*
REGION*DEPTH*SEASON	1	1	114	5.8160	0.0175*
TRT*DEPTH*SEASON	2	2	114	8.2527	0.0004*
REGION*TRT*DEPTH*SEASON	2	2	114	3.4446	0.0353*

Appendix VIII: An illustration of Penetration Resistance at 30 cm (MPa) in PRS







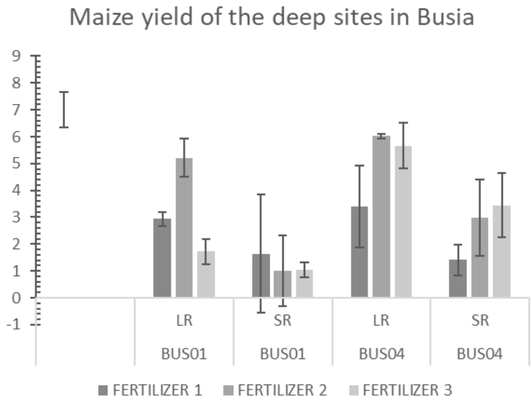


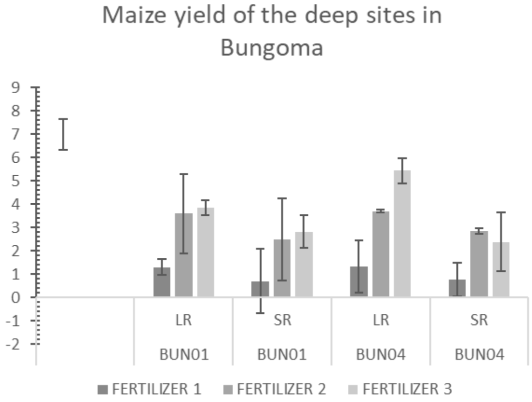
This illustrates the effect of 3 fertilizer treatments (1 - control, 2 - inorganic and organic fertilizer combination and 3 - complete inorganic fertilizer) on penetration resistance at a depth of 30 cm studied during long and short rains seasons of 2015; across 8 sites in Busia-north and Bungoma-southwest region. Four of these sites were shallow (< 20 cm when tilled) and the other deep (> 20 cm when tilled). The error bars are generated from standard error from each mean.

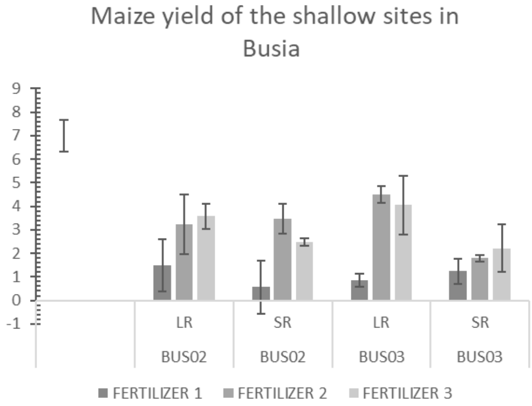
Appendix IX: ANOVA Table of Fixed effects for Maize yield in PRS

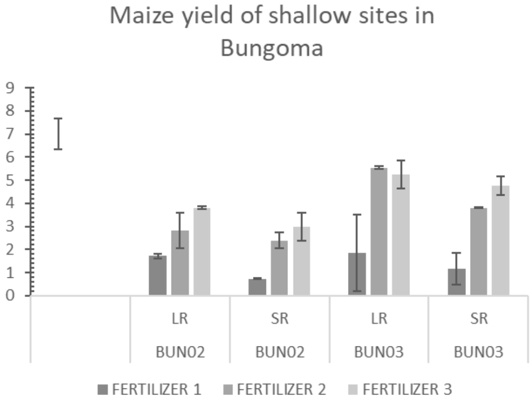
Source	Nparm	DF	DFDen	F Ratio	Prob > F
REGION	1	1	13.71	0.9423	0.3485
TRT	2	2	113.5	88.2307	<.0001*
DEPTH	1	1	3.985	0.0307	0.8695
SEASON	1	1	111.7	88.2809	<.0001*
REGION*TRT	2	2	9.8	7.8761	0.0091*
REGION*DEPTH	1	1	13.71	0.8918	0.3613
REGION*SEASON	1	1	111.7	0.0066	0.9352
TRT*DEPTH	2	2	113.5	2.8758	0.0605
TRT*SEASON	2	2	111.7	3.4750	0.0343*
DEPTH*SEASON	1	1	111.7	7.9934	0.0056*
REGION*TRT*DEPTH	2	2	9.8	1.1892	0.3448
REGION*TRT*SEASON	2	2	111.7	3.1844	0.0452*
TRT*DEPTH*SEASON	2	2	111.7	0.4110	0.6640
REGION*TRT*DEPTH*SEASON	2	2	111.7	0.8616	0.4253
REGION*DEPTH*SEASON	1	1	111.7	10.7538	0.0014*

Appendix X: An illustration of Maize yield (t/ha) in PRS



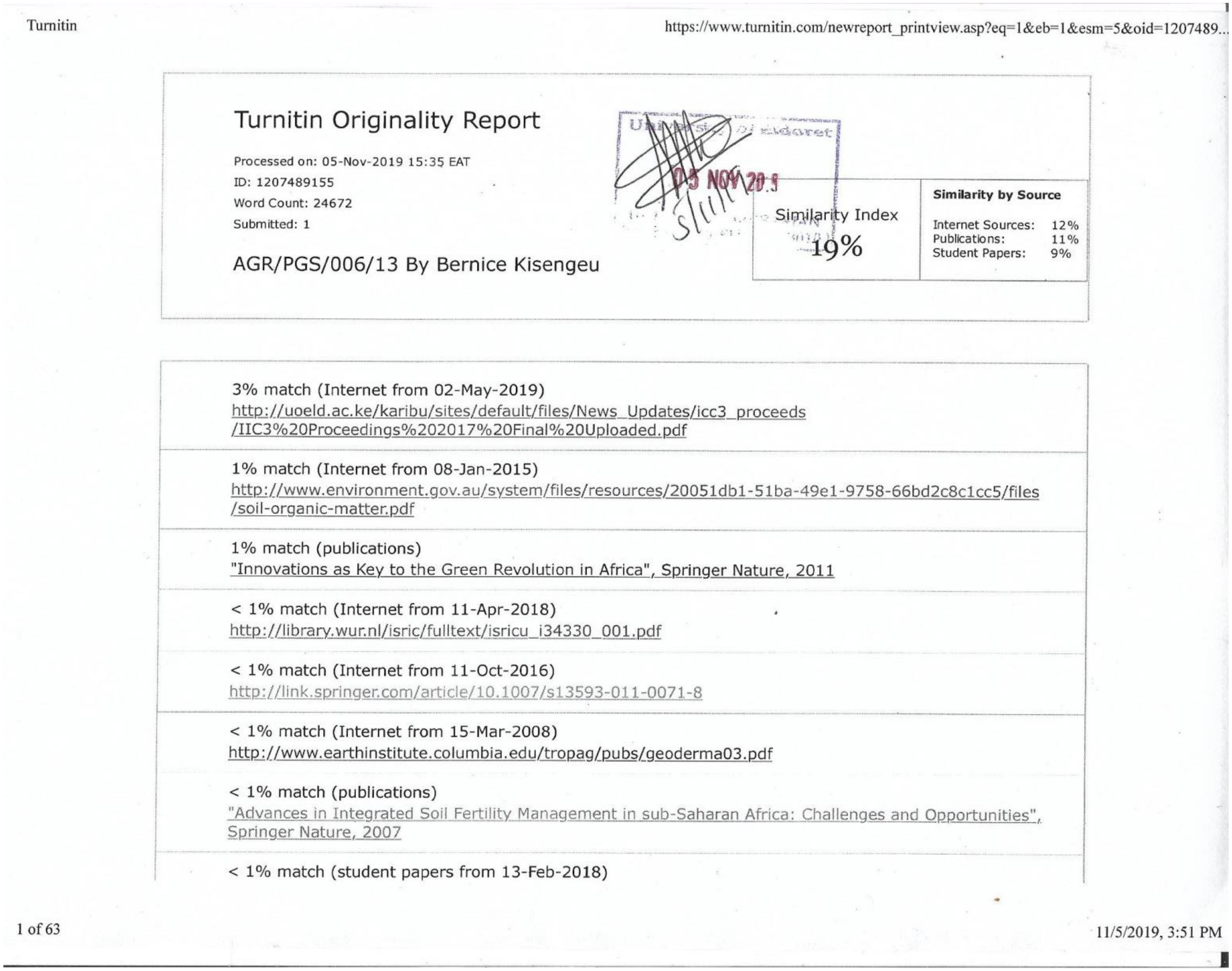






This illustrates the effect of 3 fertilizer treatments (1 - control, 2 - inorganic and organic fertilizer combination and 3 - complete inorganic fertilizer) on maize yield studied during long and short rains seasons of 2015; across 8 sites in Busia-north and Bungoma-southwest region. Four of these sites were shallow (< 20 cm when tilled) and the other deep (> 20 cm when tilled). The error bars are generated from standard error from each mean.

Appendix XI: Similarity Index/Anti-Plagiarism Report



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