EFFECTS OF CONVENTIONAL AND CONSERVATION TILLAGE ON SELECTED SOIL PHYSICAL PROPERTIES AND WATER MOVEMENT IN A VITRIC ANDOSOL IN KENYA

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DECLARATION

This thesis is my original work and has not been presented for an award of a degree in any other University.

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APPROVAL

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ABSTRACT

Soil physical and hydraulic properties determine soil productivity. Tillage alters the structure and composition of a soil consequently influencing important soil processes such as water, air, heat flux, resistance to root penetration and nutrient availability. Soil layers have distinct physical properties which influence water movement in a profile. This study investigated long term effects of conventional, conservation and no tillage systems with or without initial subsoiling on some soil physical properties and water movement in a stratified vitric Andosol. The study was carried out at Menengai Feedlots Limited, a large-scale farm at Rongai area in Nakuru District, Kenya. The experimental layout was a split plot. The main factors were conventional tillage, conservation tillage and fallow land. The sub factors were initial subsoiling and no initial subsoiling. Stepwise profiles were dug in order to expose the soil horizons at three depths; 0-30 cm, 30-60 cm and 60-90 cm. Hydraulic conductivity and infiltration rates were determined in the field using tension infiltrometer. Soil texture, aggregate stability, organic carbon and bulk density were determined in the laboratory. The soil texture in 0-30 cm and 60-90 cm was loam. Organic carbon content decreased with soil depth in all tillage systems. The decrease was significantly drastic between 0-30 cm and 30-60 cm horizon but not between 30-60 cm and 60-90 cm. The pumice horizon (30-60 cm) of the initially sub-soiled treatments had significantly high organic carbon content (3.41%) compared to none initially sub-soiled treatments (2.48%). In 0-30 cm, Aggregates of 2-4 mm size were 90%, 80% and 58% for fallow land, conservation and conventional tillage, respectively. Conventional tillage had significantly low mean weight diameter compared to the other tillage systems. Initial subsoiling significantly increased bulk density and significantly decreased hydraulic conductivity and infiltration rate of 30-60 cm. Initial subsoiling therefore affected water movement of 30-60 cm most. Conservation tillage improved the soil physical properties compared to conventional tillage. A combination of initial sub-soiling followed by conservation tillage improved the soil physical and hydraulic properties of the vitric Andosols.

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ABBREVIATIONS AND SYMBOLS

ANOVA	-	Analysis of Variance.
CTN	-	Conventional Tillage plus No Initial subsoiling
CTS	-	Conventional tillage with initial subsoiling
DOE	-	Design of Experiments
FAO	-	Food Agricultural Organisation
FSD	-	Fragment Size Distribution
GMD	-	Geometrical Mean Diameter
K_s	-	Saturated Hydraulic conductivity
MTN	-	Conservation tillage with no initial subsoiling
MTS	-	Conservation tillage with initial subsoiling
MWD	-	Mean Weight Diameter
SA	-	Soil aggregates
USDA	-	United States Department of Agriculture
ZTN	-	Fallow land with no initial subsoiling
ZTS	-	Fallow land with initial subsoiling.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Soil water is a major factor in crop production in Nakuru District, Kenya. Therefore, farmers need to manage tillage and crop residues to effectively control, store and use the limited precipitation received for crop production. Conventional tillage (various combinations of ploughing, disking and cultivation operations to control weeds and prepare a fine seed bed) has been the common practice for a long time for most large scale farms in Nakuru District. Vitric Andosols in Rongai area are inherently productive but profile stratification limits its optimal productivity. There are three horizons within the top one metre (root zone) of the profile. This

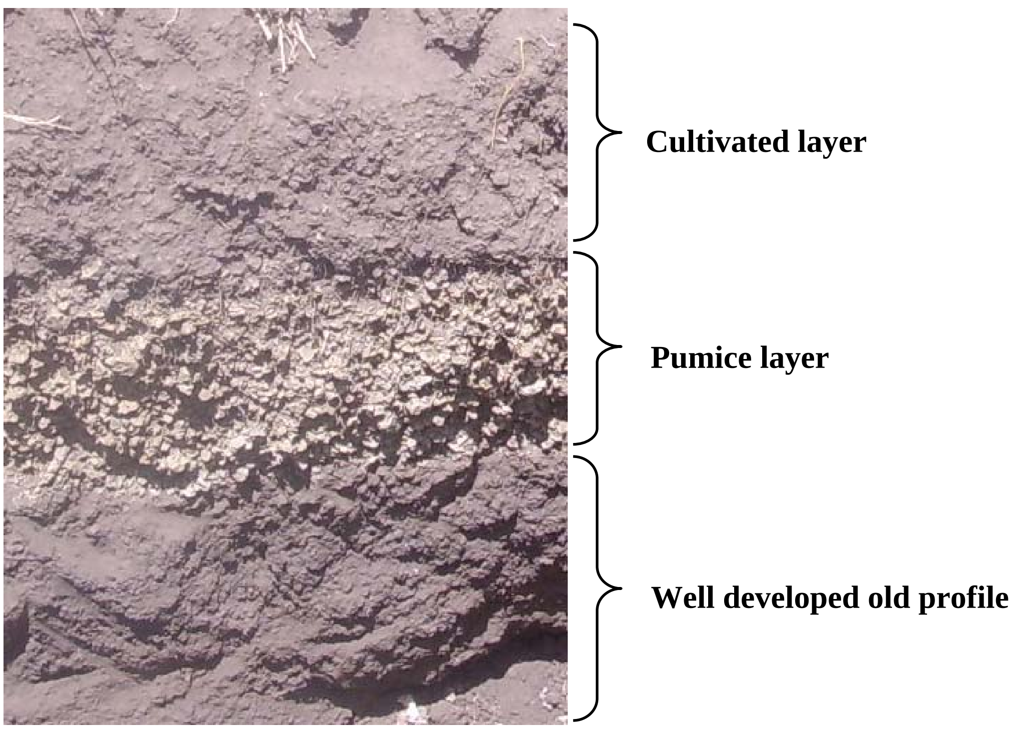

Figure 1: A typical soil profile showing stratification of the vitric Andosol, Rongai Kenya. Note the three distinct horizons.

consists of the top cultivated horizon, then a pumice horizon overlying a well developed dark coloured soil horizon (Fig. 1). The three horizons have varying physical and hydraulic properties which influence soil water retention and flow.

Soil productivity can be hindered by presence of inhibiting horizons within the profile, especially when the physical and hydraulic properties of such a horizons are not conducive for root penetration and water movement and storage (Hillel, 1980b). In such cases, subsoiling is regarded as a remedy since it breaks the inhibiting horizon. Subsoiling has successfully been applied (Yalcin and Cakir, 2006) in severely compacted soils to reduce soil resistance to water movement and provide increased root penetration. This helps the plants withstand drought conditions due to enhanced root access to higher amount of moisture accumulated in the subsoil. It also facilitates movement of soil water through soil profile.

In layered profiles, flow of water is affected by the various horizons which differ in various physical properties such as porosity (bulk density), texture, and soil structure among others (Ghildyal and Tripathi, 1987). For instance, in a scenario where a clay layer overlies a sand horizon, perhaps surprisingly, clay layers and sand layers can have a similar effect on water movement through the profile, although for opposite reasons (Hillel 1980a). The clay layer will impede flow owing to its lower saturated conductivity, while sand layer retards the wetting front (where unsaturated conditions prevail) owing to the lower unsaturated conductivity of the sand at equal matric suction. Flow of water into a dry sand layer can take lace only after the pressure head has built up sufficiently for water to move into and fill the sand (Fig. 2).

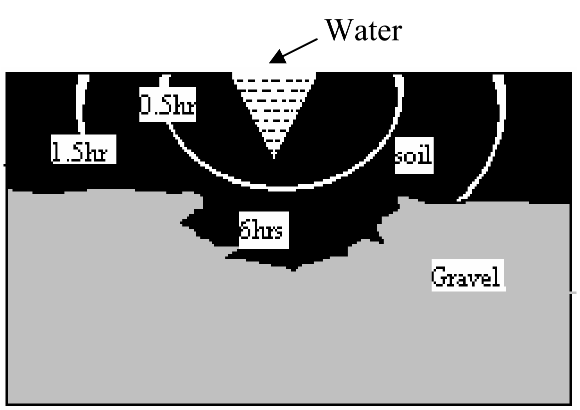

Figure 2: Flow of water in a stratified profile. Soil overlying a layer of coarse pumice/gravel (Source: Ghildyal and Tripathi, 1987).

The cumulative effect of individual distinct horizons have a great influence in the water movement through the profile and hence the hydraulic properties of the whole profile.

Quantitatively, cumulative infiltration I in the top soil-pumice interface can be expressed as shown in Equation 1 (Ghildyal and Tripathi, 1987).

$$I = K_U t + \Delta\theta\left(h_f - K_u R_c\right) In\left(1 + \frac{K_u t}{\Delta\theta h_f}\right) \qquad (1)$$

where K_u, the hydraulic conductivity of the transmission zone; t is time: $\Delta\theta$ is the difference between the water content in the transmission zone during infiltration and the initial soil water content: h_f is effective pressure head at the wetting front; R_c is a constant; *ln* is the natural log. Equation 1 can be used for calculating the cumulative infiltration as a function of time by knowing the top soil resistance and by obtaining other relevant hydraulic and soil physical properties.

The assumption that tillage improves soil properties and increase soil productivity is increasingly being called into question (Hillel 1980a). Tillage activities have both positive and negative impacts on soil structure. It alters the structure of cultivated soils and localisation of crop residues (Sillon *et al*., 2003). Tillage affects soil physical and hydraulic properties such as aggregate stability, bulk density, infiltration rate and hydraulic conductivity. These properties have great influence on soil moisture reservoir, nutrient dynamics and soil productivity. The type of tillage affects saturated hydraulic conductivity, soil moisture retention characteristics and other physical properties that enhance suitable and sustainable soil structure (Afolayan *et al*., 2003). Processes such as infiltration, evaporation, runoff erosion and chemical movement are largely influenced by surface and subsurface hydraulic properties.

In this study, the impact of various tillage systems on the soil physical properties of a stratified profile was the main consideration. Two tillage systems and a control: conventional tillage, conservation tillage and fallow land with each system either subsoiled or not were adopted. Conventional tillage whereby a deep (approximately 25 cm) primary cultivation such using mouldboard or disk plough is followed by a secondary cultivation/disc harrowing to create a fine seed bed. Its short-term effect is often generally favourable, as the implements open up soil, break up clods and incorporate the organic matter into the soil. However, over long periods, it has detrimental effects on soil structure. By opening up, mixing and stirring the soil, conventional tillage hastens the oxidation of organic matter from soils, thus weakening the aggregates and destroying the structure (Hillel 1980b). Conservation tillage is a cultivation technique where the soil remains uncultivated and seeds are directly drilled. Conservation tillage is popular in areas where rainfall causes soil erosion or where conservation of soil moisture is the objective. World wide, conservation tillage is practiced on approximately 45 million hectares (FAO, 2001). It is increasingly being used in semi-arid and tropical regions of the world (Lal 2000). As a control and for comparison purposes, a "virgin" land with some portions that were subsoiled in mid 1960's when irrigation pipes were laid in the farm was chosen. The portion of land that was chosen has been under natural pasture since then. This system is referred to fallow land throughout this study.

1.2 The Problem

The vitric Andosol found in Rongai area is characterised by a stratified profile. There are three horizons within the top one metre: the top cultivated horizon with thickness of about 30 cm, then a pumice horizon of about 30 cm thickness overlying a well developed dark coloured soil horizon at approximately 60 cm depth. The three horizons have apparent differences in their physical properties and hence influence differently the hydraulic properties of the soil. Furthermore, different tillage systems should have varying effects on soil physical properties in each horizon. In most large scale farms in Kenya such as the ones found in Rongai area and particularly in Menengai Feedlots Limited, two different tillage systems have been practiced for many years. These are conservation tillage and conventional tillage. In the mid 1960's, irrigation pipes were mechanically laid in most sections of the farm. Using three shank subsoiler capable of 70 cm depth to break the pumice horizon, irrigation pipes were laid so that they were deep enough, not to hinder mechanised operations especially tillage. During this process, the pumice horizon was broken. Despite uniform agronomic practices, apparent differences in crop performance have been observed by the farmer, whereby crop yields in subsoiled sections are higher (up to two fold) regardless of tillage system. These differences might be attributed to the presence of horizons with different hydraulic and physical properties in the profile. Different tillage systems have varying impact on the physical and hydraulic properties of the different horizons.

1.3 Justification

Many studies conducted on the impact of different tillage systems on soil physical properties have been restricted to the top 30 cm plough layer of the soil. Nevertheless the hydraulic properties of the soil horizons below the plough layer are known to influence physical behaviour of the plough layer (Sillon *et al*., 2003). The effect of various tillage practices on soil properties of a layered profile is unclear (Lopez-Bellido *et al*., 2000). Most Andosols are layered due to their mode of formation. They occur in many volcanic regions all over the world. The total area covered by Andosols is estimated at some 110 million hectares or about 1 percent of the total land surface (FAO, 2003). More than half of this is situated in the tropics. In Africa, major occurrences of Andosols are found along the rift Valley in Kenya, Rwanda, Ethiopia and in Madagascar. Layering within a profile is not confined to Andosols (FAO, 2003). Other layered soils include Fluvisols with total area coverage of approximately 350 million hectares worldwide of which more than half are also in the tropics (FAO, 2003). Andosols have a high potential for agricultural production but many of them are not utilised to their capacity mainly because of the negative effect of distinct horizons on their hydraulic properties. Andosols are fertile soils, particularly the ones in intermediate or basic volcanic ash and not exposed to excessive leaching (FAO, 2003). The management and use of stratified vitric Andosols with distinctly layered horizons has not received much attention. Although the hydraulic properties of soil are known to be highly variable in space, the combined dependence on the profile stratification and tillage systems has rarely been explored. Therefore a research study to investigate the response of vitric Andosol's hydraulic properties to tillage practices was deemed necessary.

1.4 Objectives and Hypotheses

The broad objective was to determine effects of tillage systems on selected physical and hydraulic properties of vitric Andosols.

1.4.1 Specific Objectives

1. To investigate the effects of conventional and conservation tillage systems on selected soil physical and hydraulic properties of a vitric Andosol with or without broken pumice layer.
2. To determine the horizon in a stratified vitric Andosol profile that most limits soil water movement.

1.4.2 Hypotheses

1. H_o: Conventional and conservation tillage systems have no effect on selected physical and hydraulic properties of a vitric Andosol with or without broken pumice layer.
2. H_o: Horizons in a stratified vitric Andosol have no effect on soil water movement.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Tillage Types

There is confusion in the literature concerning the terminology of tillage because many of the terms are very general and because there are very large number of different systems that vary in terms of the implements, the combination of implements and the intensity of the tillage (FAO 2008). Furthermore, different authors often use the same terms for different systems.

2.1.1 Conservation Tillage

Conservation tillage is a general term which refers to a tillage system that does not invert the soil and which retains crop residues on the surface (FAO 2008). Unnecessary inversion of the topsoil is avoided, and generally crop residues are retained as protective mulch over the surface (Phillips and Young, 1973). Conservation tillage has been found to increase soil moisture retention by improving water infiltration and diminishing soil erosion (Lopez-Bellido *et al*., 2000). Several studies on the effects/impact of conservation tillage on infiltration rate have been found to vary. Ghuman and Sur (2001), found that, at saturation (zero suction), more water was retained in the surface soil layers of minimally tilled plots, that consisted of making a small trench for seed placement with 3 Mg/ha crop residue mulch of the previous crop treatment compared to the 3.5 Mg/ha. Water intake under steady state conditions, that is, cumulative infiltration was highest (0.118 m) in the conservation tillage treatment and lower (0.105 m) in the conventional treatment. The steady state infiltration was inversely related to the bulk density values in various treatments. Bruce *et al*. (1992) reported that when water-stable aggregates formed, due to decomposition of crop residues, near the soil surface, infiltration of water into soil also increased. Vervoort *et al*. (2001) recorded an improvement on infiltration rate under conservation tillage compared to conventionally tilled soils, while other investigators (Ankeny *et al*., 1990; Gomez *et al*., 1999) could not establish any differences in infiltration rates between conventionally tilled and minimally tilled soils.

Paustian *et al*. (1997) compiled data on conservation and conventional tillage systems from several long-term field studies and found that in most cases there was an increase in total carbon content under conservation tillage. This increase was attributed to a combination of reduced litter decomposition and less soil disturbance. Reduced rates of litter decomposition may be due to a microclimate less conducive to microbial activity in the surface residue layer. The influence of soil disturbance was believed to be related to changes in aggregate dynamics, which were investigated in a study by Six *et al.*, (1999). Alvear *et al*., (2005) found that, conservation tillage increased organic matter levels in surface soil layers and thus biological activities were found to be higher in soils under conservation tillage systems than under conventional tillage systems. However, Wander and Bollero (1999) reported that the use of conservation tillage practices does not increase soil organic matter levels in all soils.

Conservation tillage systems cause an increase in the soil moisture content. This helps in conserving water in the soil. Soil conservation practices including residue management and reduced tillage, management may help in constructing or improving soil structure (Yalcin and Cakir, 2006). Aase and Pikul (1995) showed that no-till annual spring wheat crop production was the most efficient crop and soil management practice in terms of grain yield, water use efficiency, soil organic carbon and bulk density. Lopez and Arrue (1997), observed that reduced tillage (chisel ploughing) provided an efficient alternative to conventional tillage in order to maintain productivity levels in the dryland cereal growing areas of Spain. These findings are similar to those of a 3-year field study in Iran by Hemmat and Eskandari (2004), where they concluded that conservation tillage system on winter wheat crop production in a chickpea-wheat rotation was the most efficient soil management practice from the standpoint of grain yield production and water use efficiency. Their results also indicated that conservation tillage can be a more productive spring chickpea farming practice than conventional tillage.

Conservation tillage practices are advocated as the key means through which soil quality and soil organic matter can be maintained (Karlen and Cambardella, 1996). Conservation tillage practices are considered as an important component of sustainable rainfed farming (Carter, 1994; Papendick and Parr, 1997). The system is thought of enhancing soil quality (Steiner *et al*., 1988). Crop residue mulch improved soil quality in terms of organic carbon and biotic activity (Karlen *et al*., 1994). Sharratt (1996) found in one such study that a silt loam retained more water and had a higher saturated conductivity after being subject to seven years of no tillage compared with intensive tillage in interior Alaska. An increase in infiltration of water into soil has also been reported by Bruce et al. (1992). However, little work has been done on these aspects for the vitric Andosol soils.

2.1.2 Conventional Tillage

Cultivation of agricultural soils has mostly been predominantly achieved by inverting the soil using tools such as the disk or mouldboard ploughs to an average depth of 20 - 30 cm. Continued soil inversion can in some situations lead to a degradation of soil structure leading to soils composed of fine particles with low levels of soil organic matter (Holland, 2004). The term "conventional tillage" defines this type of tillage system in which a primary cultivation, such as mouldboard ploughing, is followed by a secondary cultivation to create a favourable seedbed. In addition, disk harrowing is done after ploughing. The common practice is ploughing with tractor wheel running over the bottom of the open furrow, where the soil is likely to be more compacted than the surface, and to greater depth, owing to higher moisture and lower organic matter content. Such soils are more prone to soil loss through water and wind erosion. This process can directly and indirectly cause a wide range of environmental problems. The results of a study by Denef and Six (2004), indicated despite uniform clay mineralogy, conventional tillage induced a greater modification of soil physical properties resulting in damage to soil structure. The negative aspects associated with this management system are the formation of surface crusts and ploughpans at the lower cultivation limit. The soil degradation following a decrease of soil porosity can be induced by wheel traffic.

Compaction in deeper sections of soil profile is much more difficult to rectify and hence longer lasting than compaction at the surface as reported by Hillel, (1980b) who pointed out that 90% of the soil surface may be traversed by tractor wheels during conventional tillage for closer growing crops such as cereal crops, followed by further trampling of at least 25% during combine harvesting and as much as 60% where the straw is baled and carted off. The compaction caused by all these traffic, particularly during seedbed operations, can increase bulk density to a depth of at least 30 cm.

Disturbance-related soil organic matter losses in conventional tillage versus conservation tillage may be attributed to both reduced aggregation in conventional tillage in comparison with conservation tillage and increased decomposition due to aggregate disruption (Yalcin and Cakir 2006). Six *et al*. (1998) suggested that both the level of aggregation and the rate of formation and degradation of aggregates influences soil organic matter levels.

Richard *et al*. (2001) observed that the change in soil hydraulic properties could be related to the formation of relict structural pores (Sillon *et al*., 2003) by compaction. Relict structural pores are those that have been distorted by compaction in the field during conventional tillage and traffic and which are accessible only through the necks of constricted pores.

In summary, soil compaction, disturbance-related soil organic matter losses, exposure to water and wind erosion and overall soil structure degradation are the major negative aspects of conventional tillage. The impact of conventional tillage on hydraulic and physical properties of vitric Andosol has not received much attention.

2.1.3 Pumice layer breaking

Andosols are layered due to their mode of formation (FAO, 2003). The pumice horizon is a product of volcanic deposition of ash. Pumice horizon can occur at various depths of soil profile depending on how old the profile is. Due to unique physical and hydraulic properties of pumice, it affects soil productivity. Subsoiling can be considered as a practice for recuperating the vitric Andosol by breaking the pumice layer. Subsoiling is a deep ploughing tillage system where subsoiler types of implements are operated at deeper depths (Abu-Hamdeh, 2003). Subsoiling has the effect of lifting, breaking and loosening the soil without inverting it (FAO, 2008). It is often prescribed to alleviate soil compaction. Soils that are structurally viable and stable for productive use can be identified by the structural properties that include infiltration rate and soil moisture retention (Afolayan *et al*., 2003). Soil productivity can be hindered by presence of horizons within a profile with detrimental hydraulic properties which are not conducive for both root penetration and soil water storage. In such cases, subsoiling is applied as a remedial tillage in order to break the limiting horizon within the profile. Subsoiling has been applied in severely compacted soils to reduce the soil resistance and provide an increased root depth. This helps the plants withstand drought conditions due to higher amount of productive moisture accumulated in the soil loosened deeply, especially in the subsoil (Yalcin and Cakir, 2006). It enables the roots to penetrate into a deep horizon.

In different tillage systems, an important factor having degrading effect on the properties of soils is intensive compaction by machine wheels and tillage tools (Green *et al*., 2003). In this case, subsoiling tillage system is sought as a means to loosen the pan and improve water retention. Abu-Hamdeh (2003) concluded that sub-soiling may reduce soil bulk density by an average of 2.6% in the ploughed depth of the profile. Furthermore, subsoiling, in most cases returned the soil bulk density of the compacted plots close to the original conditions.

In this study, subsoiling was applied to break the compact pumice horizon found within the soil profile. The breaking of the pumice horizon would achieve the desired effect of aiding root penetration and higher accessibility of roots to subsurface soil water. Also it will improve the bulk density of the pumice horizon, hence enhance soil water movement through the profile.

2.1.4 Fallowing

Short and long fallowing are methods of water conservation widely practised in regions of rainfed agriculture (Harris *et al*., 1989). The aim of fallowing is to maximise the storage of precipitation during the period between crops in order to provide a water reserve to supplement the erratic rainfall during the life of the following crop (Tanaka and Aase, 1987; Peterson *et al*., 1996). The secret of successful water storage at sowing time depends on improving the infiltration of rainfall, reducing water losses by evaporation and runoff, and controlling volunteer plants and weeds (Unger, 1983). Several cultural techniques can modify the efficiency of the fallow as regards moisture conservation, including soil tillage, weed control and straw mulching.

For comparison purposes and as a control, a fallow land with some portions that were subsoiled in mid sixties (more than 40 years ago) when irrigation pipes were laid in the farm was considered. The portion of land that was chosen has been under natural pasture since then. This system is referred to fallow land throughout this study.

2.2 Soil Hydraulic and other Properties in a Stratified Profile

2.2.1 Infiltration Rate

Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through the soil profile. The rate of this process relative to the rate of water supply, determines how much water will enter the root zone, and how much, if any, will run off (Hillel, 1980b). Hence the rate of infiltration affects not only the quantity of water storage in the soil, but also the amount of surface runoff.

There are contrasting responses of infiltration rate to tillage practices. For example, infiltration has been found to be slower in soils subjected to conservation tillage as compared with conventional tillage practices because soils subject to conservation tillage can be denser or less prone to crust disruption (Lindstrom *et al*., 1984). Other investigators, however, have found that infiltration is higher in soils subject to no tillage as compared with conventional tillage practices (McCaulay and Jones, 2005; Dao, 1993). The effect of tillage management on soil water movement is difficult to predict as both conventional and conservation tillage practices can either increase or decrease infiltration (McCaulay and Jones, 2005). Conventional tillage initially increases porosity and decreases bulk density. These changes may temporarily increase infiltration in tilled soils compared to soils under conservation systems. However, with time, infiltration may decrease. This change in the tilled soil may be attributed to increased compaction by tillage equipment, disturbance of macropore connectivity and structure, and settling of soil during cycles of wetting and drying (Green *et al*., 2003).

Although conservation tillage has been found to increase soil moisture and diminish soil erosion (Lopez-Bellido *et al*., 2000) by improving infiltration rate, these results are not universal. For example Vervoort *et al*. (2001) recorded an improvement in infiltration rate under conservation tillage compared to conventionally tilled soils, while Ankeny *et al*. (1990), and Gomez *et al*. (1999), could not establish any difference in infiltration rates between conventionally tilled and minimally tilled soils.

Pikul and Aase (2003) showed that water infiltration was consistently greater under sub soiling compared to conventionally tilled plots. They concluded that subsoiling tillage system improves water infiltration. This contradicts the findings of McCaulay and Jones, (2005) who reported that decreased soil disturbance in conservation tillage systems preserves macropore connectivity and increases aggregate stability. For these reasons, infiltration rates due to preferential flow may be considerably greater in soils under no-till management than in soils that are tilled. Nevertheless the benefits of subsoiling on water infiltration were reduced by conventional tillage (Pikul and Aase, 2003).

Soil physical properties can have a major influence on infiltration as well as movement of soil water to the surface during evaporation. Change in the continuity, size, and extent of pores caused by tillage strongly influences the surface and sub surface hydraulic properties of the soil (Schwartz *et al*., 2003). Although conventionally tilled cropland had an initially higher saturated conductivity, Schwartz *et al*., (2003) reported that steady-state infiltration rates were similar between conventionally tilled and no-tillage on a Pullman soil after reconsolidation and crusting of the tilled surface.

From afore review, it is clear that there are contrasting responses of infiltration rate to various tillage practices. Furthermore, the impact of tillage practices on soil physical have influence on infiltration as well as soil water movement through soil profile.

2.2.1.1 Tension Infiltrometer

Inexpensive and rapid methods for measuring the hydraulic soil properties are desirable. A tension infiltrometer is a useful instrument, which can be used under field conditions and which can measure infiltration at suctions in the range of -3 to -15 cm equivalent water column (Ankeny *et al*., 1991). It is a valuable tool to investigate the hydraulic properties of soils (Schwartz *et al*., 2003). Tension infiltrometer is robust, easy to maintain, inexpensive and allows easy setting of successive tensions. Tension infiltrometers measure infiltration rates at water pressures, which are negative relative to the atmospheric pressure. It is designed to measure the water-flow parameters of soils under a number of preset potentials. Control of the water potential at which water is supplied to the surface limits the size of pores that are actively conducting water. Measuring infiltration rates at sequentially smaller supply water potentials permits the evaluation of flow rates within several narrowly defined pore size classes and facilitates the derivation of the conductivity–potential relationship (Ankeny *et al*., 1990). Moreover, disc infiltrometer measurements across a range of water potentials can complement water retention data by providing indirect information pertaining to pore structure. Practical advantages of infiltrometer are: easy construction with detachable and interchangeable components, easy transportation and repair and easy measurement of sequence of preset potentials. In addition the general advantages of tension infiltrometers (as compared to ring infiltrometers) are faster measurements, less water requirements and minimal disturbance of soil surface. The base plate is made of 400 mesh porous nylon with a diameter of 20 cm. In practice, the tensions used vary from 3 to 15 cm.

2.2.2 Hydraulic Conductivity

Hydraulic conductivity is an important parameter of water and solute transport in soils. It is known to be highly variable in space but its dependence on soil horizonization has seldom been explored (Coquet *et al*., 2004). Hillel (1980b) defines hydraulic conductivity as the property of the conducting medium to transmit liquid. Quantitatively it is the proportionality factor K in the Darcy's equation (2) presented below (Hillel, 1980b):

$$K_s = \frac{qL}{\Delta H} \qquad (2)$$

where q is the flux density

K_s is the saturated hydraulic conductivity, cms^{-1}.

ΔH is the hydraulic head drop, cm.

L is the soil column length, cm.

Saturated hydraulic conductivity (K_s) therefore is the property of soil to transmit water under saturated conditions when all of the pores are water filled and conducting, so that continuity and hence conductivity are maximal. Processes such as infiltration, evaporation runoff, erosion and chemical movement are largely influenced by hydraulic conductivity of a soil (Chan and Heenan, 1993).

Agricultural soils are tilled to modify their structure, to enhance crop growth and water and salt movement. However, in general, the adhesion between the particles inside the aggregates decrease during soil wetting and leaching, which in turn, makes the aggregate easier to break down (Lado *et al*., 2004). Consequently, the soil tilth tends to collapse during irrigation or rainfall and this manifestation of soil structural dynamics considerably alters the soil hydraulic conductivity (Hillel, 1980a). Ben-Hur and Letey (1989) indicated that in the absence of raindrop impacts and with no deposition of kinetic energy on the soil surface, the soil permeability depends on hydraulic conductivity of the bulk soil. In contrast, when the soil surface is exposed to rain drop impact, the infiltration rate is affected by seal formation; the water drop impact causes the soil surface to break down and consequently a seal is formed. Under these conditions, infiltration rate decreases, and the runoff and soil erosion increases (Lado *et al*., 2004).

In layered profiles, flow is controlled by the layer with the conservation hydraulic conductivity value. For example, if a more conductive layer overlies a less conductive one, flow is impeded at the interface leading to pressure build up (Hillel, 1980b) which may lead to surface flooding or runoff. In different tillage systems, an important factor having degrading effect on the properties of soils is intensive compaction by machine wheels and tillage tools (Green *et al*., 2003). Sillon *et al*. (2003) showed that change in hydraulic properties could be related to the formation of relict structural pores by compaction. For example, water retained by soil would increase in a compacted soil because of contribution of volume of relict structural pores to water retention.

There are but a few studies that have examined the impact conventional and conservation tillage and soil profile stratification on soil saturated hydraulic conductivity. Furthermore, there are a lot of contradicting findings. Twenty-eight years after establishing tillage treatments on a silt loam in Ohio, Mahboubi *et al*. (1993) found that conservation tillage resulted in a higher saturated hydraulic conductivity compared with conventional tillage. Chang and Lindwall (1989) did not observe any change in saturated hydraulic conductivity of a clay loam 20 years after establishing tillage treatments in Alberta, but they did find that infiltration was greater for conservation tillage versus conventional tillage. Arshad *et al*. (1999) found infiltration of a silt loam was greater after about 12 years of conservation tillage versus conventional tillage in northern British Columbia. Schwartz *et al*. (2003), observed that hydraulic conductivities for sweep-tilled cropland on Pullman soil were greater than on conservation tillage plots throughout the entire measured range. Kribaa *et al*. (2001) recorded similar responses in comparing unsaturated conductivities under disc-tillage and conservation tillage fallow for a silty clay soil. In contrast to the above studies, Heard *et al*., (1988) found that saturated hydraulic conductivity of a silty clay loam was higher when subject to 10 years of tillage than conservation tillage in Indiana.

Therefore, based on various studies as reviewed above, and lack of consistency of their findings, it was deemed necessary to investigate the impact of conventional and conservation tillage systems on saturated hydraulic conductivity of a vitric Andosol.

2.2.3 Bulk Density

Soil bulk density ρ_b is the ratio of the mass of dried soil to its total volume. Quantitatively it is expressed as follows;

$$\rho_b = \frac{M_s}{V_t} \qquad (3)$$

where M_s is the mass of solids in grams and V_t is the total soil volume in cm^3.

If bulk density becomes too high, it can limit plant root growth (Logsdon and Karlen, 2004). For this reason, bulk density is frequently identified as an indicator of soil quality and included in many soil data sets. The specific bulk density that will adversely affect plant root growth and development depends on many factors including the parent material, soil texture, the crop being grown, and management history (Logsdon and Karlen, 2004). Problems resulting from increased loads on the soil surface like soil deformation, compaction and destruction of soil structure (Lowery and Schuler, 1991) involve significant interrelationships between many physical and biological properties of soil. Soil compaction leads to soil structure degradation, thereby reducing the size and number of macropores. Associated with these changes are increased bulk density and soil resistance to root penetration. In compacted layer, water, nutrients and air flow towards the plant roots are restricted (Akinci *et al*., 2004). One of the most frequently used measures of soil compaction is soil bulk density (Abu-Hamdeh, 2003). Ghuman and Sur, (2001) found that bulk density in the 0-0.1 m soil layer was significantly lower by about 0.05 g/m^3 in minimally tilled treatment than in conventionally tilled treatments. At the 0.075 m depth, there was no difference in bulk density between conservation tillage and conventional tillage treatments. However, at 0.125 m depth, bulk density was significantly lower in the conservation tillage than the conventionally tilled plots. This was due to compaction and hence development of a plough pan in the conventionally tilled treatment in this zone. Crop residue mulch has been reported to improve soil quality in terms of organic carbon and biotic activity (Paustian *et al*., 1997), and this might be the cause for the lower bulk density, particularly near the soil surface in the no-till plots of the study by Ghuman and Sur, (2001).

Elimination of soil mechanical loosening caused by tillage operations is responsible for the increase in soil bulk density in conservation tillage. Schwartz *et al*. (2003) observed a significantly greater bulk density of the surface 0.05 m of soil on re-established grassland than on cropland. For the 0.05–0.08-m depth, cropland bulk densities were lowest compared to the other two land use treatments, reflecting the loosening effect of tillage. At greater depths, significant differences in bulk density were not detected among land use treatments Schwartz *et al*. (2003).

Hillel (1980b) pointed out that mechanized farm operations led to increased bulk density and hence soil compaction. Abu-Hamdeh (2003), on the other hand, concluded that sub-soiling reduced soil bulk density by 2.6% to a depth of approximately 40 cm. Furthermore, Abu-Hamdeh (2003) this investigator showed that subsoiling in most cases returned the soil bulk density of the compacted plots close to the original conditions. Pikul and Aase (2003), showed that repeated conservation tillage of sandy loam soils in eastern Montana increased bulk density at a depth of 10 cm causing hard pans.

Due to variations in composition and morphological characteristics in different horizons of a stratified soil profile, there will be likelihood of bulk density to vary too. Also, bulk density has direct influence of soil water movement through the profile. Tillage practices and their extent of physical manipulation of soil affect bulk density. Hence, bulk density is considered in this study due to the effect induced by tillage and ultimate impact on soil water movement through stratified soil profile.

2.2.4 Aggregate Stability

Soil aggregation refers to the binding together of soil primary particles to form compound particles of various shapes and sizes, known as aggregates. The formation and maintenance of stable aggregates is an essential feature of soil tilth. Soil tilth is a qualitative term used by agronomists to describe that highly desirable, yet unfortunately elusive, physical condition in which the soil is optimally loose, friable and porous assemblage of aggregates permitting free movement of water and air, easy cultivation and planting and unobstructed germination and root growth (Hillel, 1980b).

Soil aggregation may be determined by mean weight diameter (MWD), geometric mean weight diameter (GMD) and aggregate stability (AS, %) indices, which are obtained by fractioning the soil material into aggregate classes either by dry sieving as proposed by Le Bissonnais (1996) or by wet sieving (Kemper and Chepil, 1965). These indices are sensitive to soil management practices and physical conditions (Pinheiro *et al*., 2004). Geometric mean diameter is calculated as follows.

$$GMD = \exp\left(\frac{\sum w_i \ln x_i}{\sum w_i}\right) \qquad (4)$$

where w_i is the weight of the aggregates of each size class g and $\ln x_i$ the natural logarithm of the mean diameter of size classes.

In a review of many field trials of conservation tillage on light textured soils in southern Australia, Chan *et al*. (2002), observed that although storage of soil organic carbon is greater in sites that are direct drilled, compared to conventional cultivation, the differences are only significant in higher rainfall areas (>500 mm), and that soil quality is likely to remain fragile in lower rainfall zones. Increases in soil carbon content are usually limited to the topmost soil layer. Organic matter increases soil aggregation due to organic carbon produced by decomposition. Additions of organic matter lead to increase in the macropores (Garnier *et al*., 2004).

In agriculture, the soil is disturbed periodically under tillage; it is fractured into clods and fragments as well as having its natural aggregates separated. It is pulverized to a range of aggregate sizes that varies with the purpose of the tillage operation (Marshall and Holmes., 1979). Hewitt and Dexter (1980) reported that aeration and porosity in conventionally tilled plots were 30% higher than in minimally tilled soils. Mean void size was 17% higher, while mean aggregate size was 30% larger in minimally tilled than conventionally tilled plots.

Ghuman and Sur, (2001) reported a significantly greater MWD of soil aggregates in the minimally tilled as compared to conventionally tilled treatments. Similarly, geometric mean diameter was significantly higher in the minimally tilled than the conventionally tilled treatment. Angers *et al*. (1993) positively correlated the improvement in soil structure stability with microbial biomass and water soluble carbohydrates, both of which also influence infiltration. Further, aggregation improvement in the minimally tilled treatment was also associated with the significant increase in organic carbon content and protection of the surface layer by crop residue mulch against the action of falling raindrops (Lal, 1989). Their results indicated that under conservation tillage treatments the aggregation of the surface layers improved (Ghuman and Sur, 2001).

The decline in the size of aggregates with conventional tillage could be attributed to mechanical disruption of macroaggregates, which may have exposed soil organic matter previously protected against oxidation. The lack of residue coverage, promoting the erosion of fine clay and organic matter particles (Pinheiro *et al*., 2004), would likely have been responsible for the lowest organic carbon content and aggregate stability under conventional tillage. The highest organic carbon content in conservation tillage was related to the higher input and renovation of above ground and root biomass. Roots greatly influence the formation and stabilization of soil aggregates by their extensive networks, which penetrate the soil and tend to enmesh soil aggregates (Hillel, 1980b).

In a study by Kushwaha *et al*., (2001), maximum increase in mean weight diameter (MWD) was recorded in the conservation tillage treatment, and less marked increase in the 2.0–4.75mm size class. However, the proportion of soil in the lower size classes (<0.053–2.0 mm) was distinctly reduced in residue retained compared to residue-removed treatments. Aggregate stability was evaluated as MWD in various tillage and residue treatments. Residue retention with conventional tillage increased the MWD of aggregates by 62% more than control. Tillage reduction alone, from conventional to conservation tillage condition increased the MWD of aggregates by 27–45% compared to the control. Residue retention along with tillage reduction increased MWD by 71–98% more than control. Tillage reduction combined with residue retention increased the proportion of macroaggregates in the soil compared to the control. The proportion of microaggregates in the soil, on the other hand, was less in residue retained compared to residue-removed treatments. Tillage reduction alone also increased (14–17%) the proportion of macroaggregates in soil, but the degree of increase was less than that recorded in residue retained treatments. Tillage reduction decreased considerably the proportion of microaggregates in the soil (Kushwaha *et al*., 2001).

Several models have been proposed in order to correlate aggregate dynamics to a change in soil organic matter. Tisdall and Oades (1982) presented a conceptual, hierarchical model for soil aggregate formation. This model describes the association of organic matter with three different soil physical units: silt and clay particles, microaggregates (<250µm), and macroaggregates (>250 µm). This model was applied by several investigators to explain the often observed accumulation of soil organic matter under no-tillage versus conventional tillage systems (Beare *et al*., 1994). According to Tisdall and Oades (1982), cultivation causes a reduction in the amount of macroaggregates, but it does not affect microaggregate stability.

By studying aggregate stability it is possible to quantify whether or not the soil management system is ameliorating the natural soil properties and the land capability for agriculture (Pinheiro *et al*., 2004). Soil aggregation is important for the resistance of land surfaces to erosion, it influences the ability of soils to remain productive. Soil aggregate distribution has been used as a conservation index for clayey Oxisols (Castro Filho *et al*., 2002). Modification of some soil attributes i.e. soil aggregate distribution, can be used to evaluate the soil physical condition, determining whether a certain soil management system for crop production might improve its natural characteristics or the land capability (Pinheiro *et al*., 2004).

Conservation and conventional tillage systems directly affect aggregate stability of soil. Furthermore, aggregate stability have influence on soil water movement through soil profile. As Pinheiro *et al*., (2004) pointed out, it is possible to quantify the impact of soil management system on land capability for agricultural use.

2.3 Effects of Organic Matter on Studied Physical Properties

One of the most important components of the soil is the organic matter. This strongly influences soil structure, soil stability, buffering capacity, moisture retention, biological activity and nutrient reserve and its availability. It ultimately determines the risk of erosion (Ryan *et al*., 2001; Holland, 2004). Soil organic matter represents the remains of roots, plant material and soil organisms in various stages of decomposition and synthesis, and is variable in composition though occurring in relatively small amounts (Ryan *et al*., 2001). Organic matter is considered one of the main agents favouring soil aggregation. Part of the aggregate size variation and therefore, the aggregation indices in tropical soils can be attributed to variations in soil organic matter (Pinheiro *et al*., 2004). Soil organic matter has been increasingly considered as an indicator of soil quality, one of the components of biosphere sustainability and stability. Quantity and quality of soil organic matter and its major component, humus, is influenced by management practices and especially by soil tillage. Quiroga *et al*. (1998) showed that soils with higher levels of organic matter had lower susceptibility to compaction and greater aggregate stability, and that organic matter levels were strongly influenced by soil management. Soils low in organic matter and nutrients exhibit increased susceptibility to degradation upon cultivation especially if management of these soils is inappropriate (Burt *et al.*, 2001).

In a study by Ghuman and Sur (2001), organic carbon content was significantly increased in minimally tilled treatments more than that of conventionally tilled treatment in the surface 0.02 m layer. The increase of organic carbon in the minimally tilled treatments was probably caused by less oxidation of in situ organic matter roots, due to the absence of tillage (Edwards, *et al*., 1992) and absence of soil redistribution. Due to reduced soil erosion, surface runoff and mineralization of organic matter, organic carbon content is usually greater in soils managed with conservation than with conventional tillage (Dalal, 1989). Conventional tillage practices and removal of crop residues can lead to a reduction in soil organic matter due to accelerated decomposition and loss of organic matter rich topsoil thereby adversely affecting soil properties (Kushwaha *et al*., 2001).

Pinheiro *et al*., (2004) found out that, there was a high significance of carbon content under conservation tillage than under conventional tillage in both whole soil and aggregate fractions. Furthermore, carbon was concentrated more in the surface (0–5 cm) under conservation tillage, while the distribution was more uniform under conventional tillage. Soil disruption by mechanical tillage and lack of conservation practices caused a reduction in total organic carbon content and soil aggregation, indicating greater potential for soil structure degradation. It was further realised that, among the tillage systems, aggregate distribution indices were greater for conservation tillage than conventional tillage system. However, the reference plot with grass coverage had the highest indices for aggregation, total organic carbon and carbon concentration in the aggregate size classes. Intensive cultivation of soil break down soil organic matter producing carbon dioxide and hence lower total carbon in the soil. By building soil organic matter the adoption of conservation tillage, especially if combined with the return of crop residues, can substantially reduce carbon emissions (Holland, 2004). In other words, it can reduce mineralization rate of organic matter, hence lower soil nutrients loss and increase soil stability, soil fauna and microbes.

Kushwaha *et al*. (2001) concluded that, tillage reduction in association with residue retention caused 17% increase in the amount of organic C than tillage reduction alone. Kushwaha *et al*. (2001), further observed that, soil disturbances caused by tillage operations accelerate organic matter decomposition. The combined effect of tillage reduction and residue retention on the accumulation of soil organic carbon was 17-28 % than the effects of either tillage reduction or residue retention alone. Soil structure depends on the amount and quality of organic matter (Dormaar and Carefoot, 1996).

Emmerson (1977) suggested that organic matter stabilized the aggregates mainly by forming and strengthening bonds between the particles within them. Tisdall and Oades (1982) classified these organic binding agents into: transient - mainly polysaccharides, temporary - roots and fungal hyphae, and persistent - resistant aromatic components. Cultivation results in loss of labile organic matter which binds microaggregates into macroaggregates and the inter-microaggregates organic matter is responsible for the long-term fertility of native soils (Kushwaha *et al*., 2001).

Although many studies have determined the effects of organic matter content on aggregate stability and on mechanical properties of soil (Kern, 1995; Franzluebbers, 2002; and Lado *et al*., 2004), few have investigated the effect of organic matter content on soil water movement. Organic matter is important in this study because of its role in the stabilization of soil structure as exhibited by significant positive correlation between organic carbon and aggregate stability in a study by Kushwaha *et al.* (2001) and hence sol water movement. In addition, different tillage practices have varied impact on soil organic matter.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Site Characteristics

The study was carried out at Menengai Feedlots Limited, a large-scale farm at Rongai area in Nakuru District, Kenya (Fig. 3) from early February to late March 2006.

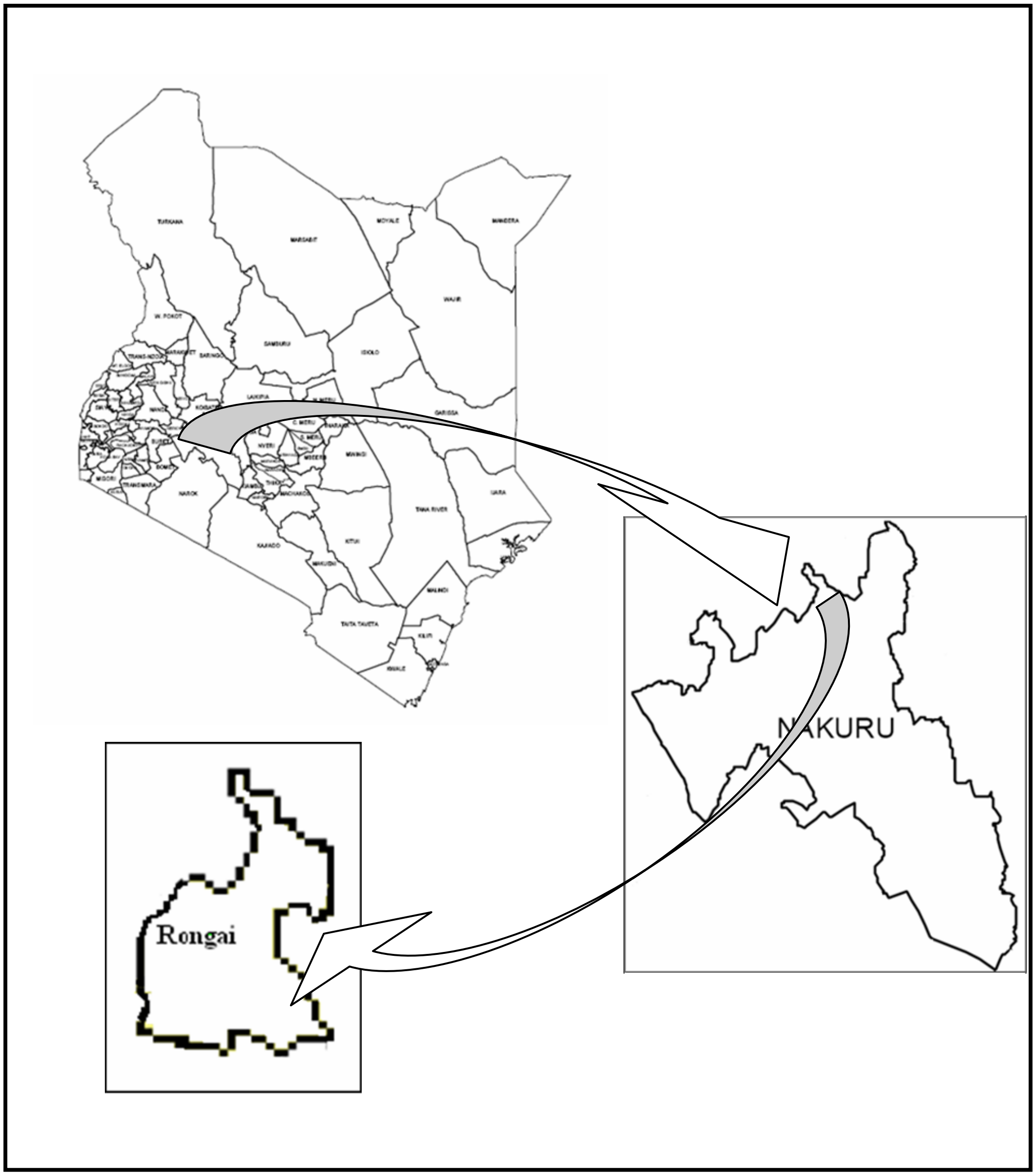

Figure 3: Map showing the study area: Rongai Division, Nakuru District, Kenya

The farm is located approximately 00°13'S and 35° 58' E with an altitude of 2068 m above mean sea level. The soils are derived from volcanic ash and have been classified as vitric Andosols by Jaetzold and Schmidt, (1983) following FAO UNESCO (1974). The area has a mean annual rainfall of approximately 1200 mm. Rain fed large-scale cereal (wheat) production is the dominant land use in the region and the various tillage systems have been in use for more than five years.

3.2 Experimental Design

Three tillage systems, in split-plot design with three replications were investigated. The main plot treatments were: conservation and conventional tillage systems and fallow land as a control. The subplots treatments were either initial subsoiling or no initial subsoiling. The experimental layout was as shown Fig. 4 below;

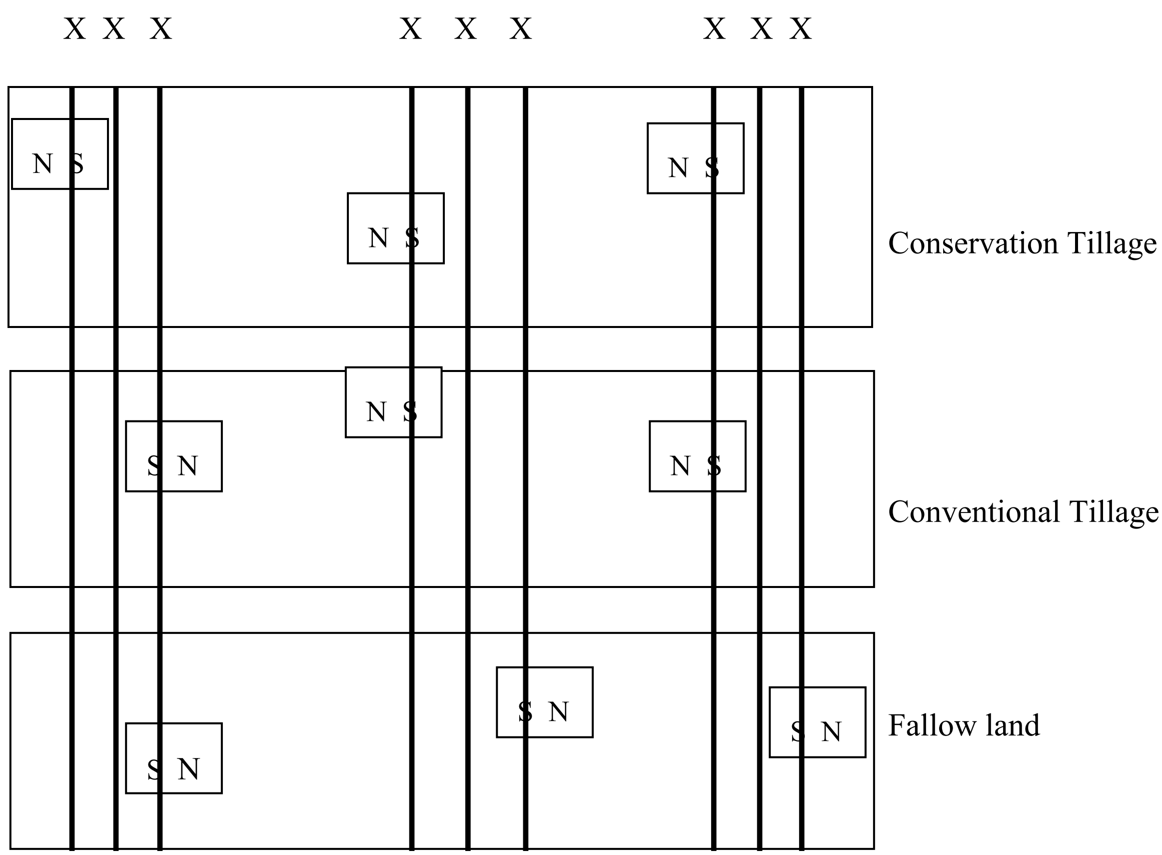

Figure 4: Sketch of Experimental Layout: where X are sections the subsoiler passed, S represent initial subsoiling and N, no initial subsoiling.

3.3 Field Treatments

In the mid sixties, water pipes were laid in most sections of the farm. The process involved breaking of the pumice (30-60 cm depth) horizon as the pipes were laid about one metre deep. In the process of refilling the ditches the pumice particles got mixed with mineral soil. This activity simulated subsoiling. Therefore, initial subsoiling sub-factor treatments were carried out along these sections in all selected plots that were under investigation as shown in Fig. 4. Conventional tillage involved the use of disc plough in combination with disc harrow to adequately pulverise the soil to a level sufficient for seed germination and consequent crop establishment. In conservation tillage, herbicides were used to control weeds before direct drilling of seeds. The main objective of conservation tillage being preservation of soil moisture. As a control, and for comparative purposes, a relatively undisturbed field was chosen. These undisturbed field is being referred to as fallow land in this study. It had sections that were subsoiled about four decades ago when pipes were being laid and has been under natural pasture since then. Six treatment combinations were applied as follows:

(i) Conservation tillage with initial subsoiling,

(ii) Conservation tillage without initial subsoiling,

(iii) Conventional tillage with initial subsoiling,

(iv) Conventional tillage without initial subsoiling,

(v) Fallow land with initial subsoiling and

(vi) Fallow land without initial subsoiling.

3.4 Laboratory Procedures and Methods

3.4.1 Soil Samples Preparation

Disturbed soil samples were air-dried and the replicates bulked. Large clods were broken by hand and sieved to pass 4 mm aperture for aggregate stability determination, through 2 mm aperture for texture determination and through 0.5 mm aperture for organic carbon determination. The sieved soils were collected, sub-sampled and stored to await specific analyses.

3.4.2 Soil Texture

Soil texture was determined using hydrometer method as described by Ryan *et al*. (2001). Fifty grams of air dried <2 mm soil samples were weighed into 400 ml beakers, saturated with distilled water and 10 ml of dispersing chemical (10% sodium hexametaphosphate) solution added. 10 ml of hydrogen peroxide was added to remove other cementing agents. They were allowed to stand for 10 minutes. The suspension was transferred into dispersing cups. About 300 ml of distilled water was added. The suspension was mixed for 2 minutes using high-speed electric mixer, transferred into sedimentation cylinder and water added to bring the volume to one litre. Some time was allowed for the sedimentation to equilibrate thermally and temperature (T_1) recorded. The plunger was inserted into the cylinder and the contents thoroughly mixed. Strong upward strokes of the plunger were applied to dislodge sediment from the bottom of the cylinder. Timing was started immediately the plunger was removed. After 30 seconds, hydrometer was gently lowered into the suspension and the first reading (R_1) taken after 40 seconds. The hydrometer was removed, rinsed, and wiped dry. The cylinder was allowed to stand undisturbed for almost 2 hours. After 1 hr 50 min., hydrometer was carefully reinserted the next reading (R_2) was taken after exactly 2 hours. Temperature (T_2) readings were also taken. Percent sand, clay and silt were calculated by applying equations 5, 6 and 7.

$$\%\ \text{Sand} = \left(\frac{50 - R_1}{50}\right) \times 100 \qquad (5)$$

$$\%\ \text{Clay} = \left(\frac{R_2}{50}\right) \times 100 \qquad (6)$$

$$\%\ \text{Silt} = 100 - \left(\%Clay + \%Sand\right) \qquad (7)$$

where R_1 and R_2 are the hydrometer readings after 40 s and 2 hours respectively.

Based on these calculations, soil samples were assigned texture classes using USDA classification scheme textural triangle.

3.4.3 Organic Carbon

Organic carbon content was determined using modified Walkley and Black wet oxidation procedure described by Ryan *et al*. (2001). Half a gram of air dried soil passed through 0.5 mm sieve were weighed into 500 ml wide mouth conical flasks and 10 ml of 1 N potassium dichromate added into the flasks using a burette. In a fume cupboard, 15 ml concentrated sulphuric acid was rapidly added directing the stream into the suspension. The flasks were swirled gently at first until all soil and reagents mixed and then more vigorously for about one minute. They were then allowed to stand for exactly 30 minutes. About 150 ml of distilled water was added and allowed to cool, after which 10 ml 85% orthophosphoric acid and finally 10 drops diphenylamine indicator were added. The solutions were titrated with 0.5 N ammonium ferrous sulphate. Percent oxidisable organic carbon was calculated as:

$$\text{\% Organic Carbon} = \frac{V_{Blank} - V_{Sample} \times M \times 3 \times 10^{-3} \times 100}{W_t} \qquad (8)$$

where, V_{Blank} is the volume (ml) of ferrous ammonium sulphate solution required to titrate the blank, V_{Sample}, volume (ml) of ferrous ammonium sulphate solution required to titrate the sample, W_t, weight (g) of air-dry soil, 3 x 10^{-3} is the equivalent weight of carbon and 100 is the percentage. M, molarity of ferrous ammonium sulphate solution (approximately 0.5M i.e. $10/V_{blank}$).

3.4.4 Aggregate Stability

Aggregate stability was determined by the fast wetting method proposed by Le Bissonnais (1996) and modified by Wakindiki and Ben-Hur, (2002). After air drying, the samples with aggregate size of 2-4 mm were oven dried at 40^{o}C for 24 hours so that they were at a constant matric potential. Five grams of oven-dry aggregates were gently immersed in a beaker containing 50 cm^3 of distilled water for 10 minutes. The water was then sucked off with a pipette. The soil material was transferred to a 63 µm sieve that had previously been immersed in ethanol to reduce slaking effect and gently moved up and down in ethanol five times to separate fragments less than 63 µm from those greater than 63 µm. The greater than 63 µm fraction was collected from the 63 µm sieve, oven dried and gently dry-sieved by hand on a column of six sieves: 2000 µm, 1000 µm, 500 µm, 180 µm, 100 µm and 63 µm. The weight of each size fraction was calculated as follows; the fraction less than 63 µm was the difference between initial weight and the sum of the weights of the six other fractions. The aggregate stability of each breakdown mechanism was expressed by calculating the mean weight diameter (MWD) of the seven classes, which is the sum of the weight fraction of soil remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent mesh:

$$MWD = \sum_{i=1}^{7} \bar{x}_i w_i \qquad (9)$$

where, w_i is total weight fraction of aggregates in the size class *i* with a diameter $\bar{x}_i$.

Because pebbles of the same size as the 2000 µm aggregate size class (2000 µm aggregate-sized pebbles) is unlikely to be a part of an aggregate, it was necessary to correct for the aggregate-sized pebbles content (Elliott *et al*., 1991). This was important in the experiment, because the soil samples were composed of substantial >2000 µm rock fragments. Therefore, after weighing the >2000 µm size fraction of the aggregates, they were carefully transferred into dispersing cups. About 300 ml of water was added. The suspension was stirred for 2 minutes using high-speed electric mixer to disperse the macroaggregates. The sub-sample (after dispersion) was sieved through 2000 µm sieve and washed with water until the water passing through the sieve was clear. The pebbles were then oven dried and weight taken. Pebbles - corrected aggregation (%) was determined as a proportion of total air dry soil mass:

$$\text{Pebbles-corrected aggregation} = \frac{(W_{ASF} - W_{ASP}) \times 100}{\sum W_A} \qquad (10)$$

where W_{ASF} is aggregate size fraction, W_{ASP}, Aggregate sized pebbles and $\sum W_A$ is all fractions (pebble corrected weights).

3.4.5 Bulk Density

The undisturbed cores were transported to the laboratory and placed in the oven at 105°C until constant weight was attained. The weights (W_2) of the soil samples were taken. The bulk density was calculated using Equation 11.

$$\text{Bulk density (g/cm}^3\text{)} = \frac{W_2 g - W_1 g}{V cm^3} \qquad (11)$$

where $W_1\,g$ is the weight of the core ring, $W_2\,g$, the weight of the oven dried sample plus core ring and $V\,cm^3$ volume of the core ring.

3.5 Field Practices

3.5.1 Soil Sampling

Three soil profiles per tillage system were randomly opened in the site. The profile was approximately 1 meter deep in a staircase pattern shown in Fig. 5. Three undisturbed core samples (5 cm diameters and 5 cm height) were collected from each of the three profile layers.

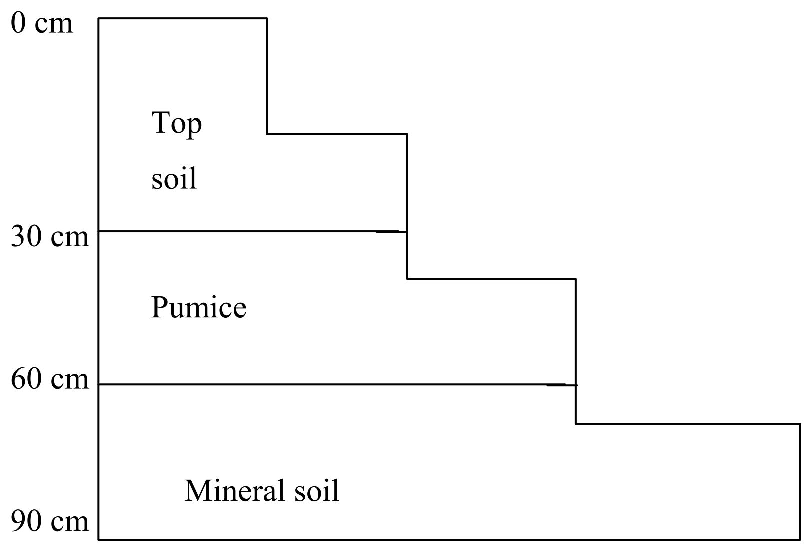

Figure 5: Sketch of the longitudinal section of the profile layout as was dug in the field for soil sampling.

Prior to sampling, the soil was moistened in order to minimise its disruption during sampling. Standard core rings of known weights (W_1) were driven into the soil using a double cylinder, hammer driven core sampler. Excess soil protruding from the bottom and the top of the cores were trimmed using a knife. This ensured that the top and the bottom of the sample were in flush with the ends of the core rings and thus the volume of soil was equal to internal volume of the core ring. These undisturbed samples were used for bulk density determinations. Disturbed soil samples were collected from each of the three horizons of all the profiles. The samples were transported to the laboratory for soil texture, soil carbon and soil aggregate stability determinations.

3.5.2 Infiltration Rate

Infiltration rate was determined using a tension infiltrometer (with a 20 cm diameter infiltrometer disc) (Fig. 6). About 1-2 cm of soil surface was removed on a 40 cm diameter area in sections where determinations were to be done using a pointing trowel. The metal ring was gently pressed into the prepared surface after which a thin layer of fine sand was placed and levelled with a straightedge. The sand acted as a contact material to facilitate a good contact between the disc and the soil surface. The infiltrometer disc was centred onto the ring and the device gently pressed down onto the sand. It was ensured that the bottom of the bubble tower and the nylon membrane were at the same elevation during measurement in order to maintain equal tension at the membrane and the set tension with air entry tube. Carpenter's level was used to set the elevation. After removal of the sand outside the ring and the ring itself, infiltration was quickly started to prevent air bubbles from entering the disc through the membrane. Infiltration rate measurements were taken at two tensions; that is -5 cm and -15 cm as recommended in the instruction manual (soil measurement systems). These readings were to be used to determine both hydraulic conductivity and infiltration rates. Infiltration rate was measured using tension infiltrometer at -5 cm tension. Upon reaching steady state (i.e. when the water level in the supply tube fell at an average rate), the readings were recorded with time.

For each determination, steady state unconfined infiltration rate into soil from a circular 20 cm radius source was derived following Wooding's (1968) algebraic equation (12) thus;

$$Q = \Pi r^2 K\left[1 + \frac{4}{\Pi r \alpha}\right] \qquad (12)$$

where Q was the volume of water entering the soil per unit time (cm^3/hr); K was the hydraulic conductivity (cm^3/hr); r was the radius of the tension infiltrometer disc and α was a constant.

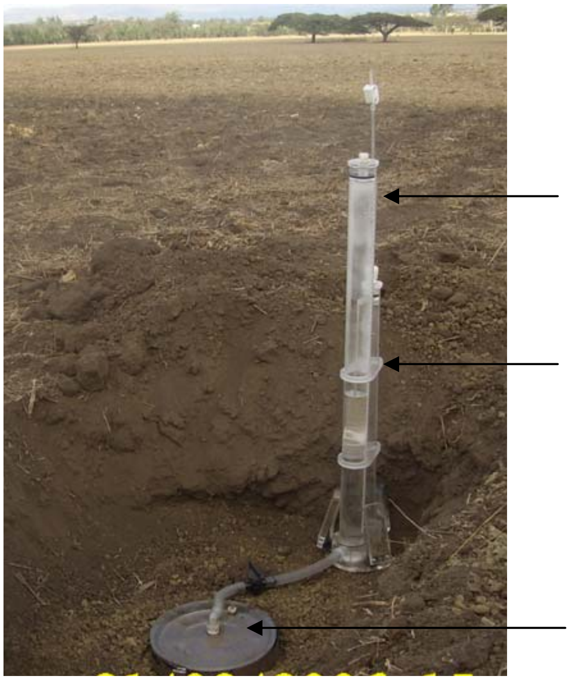

Figure 6: Tension Infiltrometer

Tension infiltration data were used to evaluate the saturated hydraulic conductivity (*Ks*) in combination with sorptive number (α) given by Gardner's (1958) exponential model (Equation 13) of the unsaturated hydraulic conductivity using Wooding's (1968) analytical solution.

$$K(h) = K_{sat} \exp(h\alpha) \qquad (13)$$

where *h* is the matric potential or tension at the source (cm). The value of *h* is normally negative corresponding to a tension at the water source; however, it can also be zero. It is assumed that unsaturated hydraulic conductivity of the soil varies with matric potential *h* (cm) as proposed by Gardner (1958) in Equation 13.

Analyses required measurements using a single disc diameter but with multiple tensions as recommended by Ankeny *et al*., (1991) and Schwartz *et al*., (2003).

3.5.3 Hydraulic Conductivity

Hydraulic conductivity was determined from the readings taken with the tension infiltrometer. Wooding's (1968) algebraic equation (12) for approximating unconfined infiltration rate in conjunction with Gardner's (1958) Equation 13 based on one particular conductivity pressure relation was applied in the determination. Equation 12 was used to calculate hydraulic conductivity in conjunction with Equation 13 as proposed by Gardner (1958). It assumes that the unsaturated hydraulic conductivity of the soil varies with matric potential h (cm). K_{sat} is the saturated hydraulic conductivity (cm/hr). For unsaturated soil, and upon replacing K in (12) with K_{sat} exp ($h\alpha$), and after substituting h_1 and h_2, respectively for h in the combined equations 14, 15 and 16 are obtained.

$$Q(h_1) = \Pi r^2 K_{sat} \exp(h_1 \alpha)\left[1 + \frac{4}{\Pi r \alpha}\right] \qquad (14)$$

$$Q(h_2) = \Pi r^2 K_{sat} \exp(h_2 \alpha)\left[1 + \frac{4}{\Pi r \alpha}\right] \qquad (15)$$

dividing (5) by (1) and solving for α yields,

$$\alpha = \frac{In[Q(h_2)/Q(h_1)]}{h_2 - h_1} \qquad (16)$$

because $Q(h_1)$ and $Q(h_2)$ are measured, and h_1 (tension at -5) and h_2 (tension at -15)are known, α can be computed directly from Equation 16.

With known α , K_{sat} can be calculated from equation 14 or 15.

Once K_{sat} and α were known, their values were substituted in equation 12, yielding the relationship between hydraulic conductivity and tension for the soil. This relationship was used to calculate hydraulic conductivity at -5 and -15 cm tensions.

3.6 Data Analysis

Statistical analysis was carried out using design of experiment (DOE) and Fit Model procedure of the JMP IN 5.1 (Sall *et al.*, 2003) statistical package software. The data was subjected to analysis of variance using the General Linear Model for a split-plot design to obtain an F value of the effect of the model for each treatment. Regression and correlation analyses were done to evaluate relationships between the different soil parameters and tillage system treatments. Significance of differences between treatments means were examined using Student's t Least Mean Square differences procedure at the 5% level of significance (Steel *et al.*, 1997). The statistical model used was:

$$Y_{ijk} = \mu + \rho_i + \alpha_j + \gamma_{ij} + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk} \qquad (17)$$

i = 1, 2, 3; j = 1, 2, 3; k = 1, 2.

where Y_{ijk} was hydraulic conductivity, aggregate stability, infiltration rate, or bulk density of the soil, μ was Grand mean, ρ_i is i^{th} block effect, α_j was j^{th} tillage systems, γ_{ij} was error on tillage system, β_k was k^{th} initial subsoiling, $(\alpha\beta)_{jk}$ was interaction effect of the j^{th} tillage system and k^{th} initial subsoiling, ε_{ijk} was random error component. The γ_{ij} and ε_{ijk} were normally and independently distributed about zero means with a common variance σ^2.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

The results as shown in Table 1 indicate that the soil at the site is loamy for all the treatments at the top 0-30 cm and 60-90 cm depths. The 30-60 cm depth horizon was mainly composed of pumice particles.

Table 1. Soil textural classes for the various treatments at the experimental site

Tillage system	No initial subsoiling				Initial subsoiling			
	Depth (cm)	Sand ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Textural class*
Conservation	0-30	460	160	380	440	80	480	loam
Conservation	60-90	340	240	420	320	260	420	loam
Conventional	0-30	440	120	440	440	120	440	loam
Conventional	60-90	320	220	460	320	260	420	loam
Fallow	0-30	480	140	380	380	200	420	loam
Fallow	60-90	360	200	440	360	200	440	loam

* USDA texture classification

4.1 Organic Carbon

The effect of various tillage systems and initial subsoiling on percent organic carbon levels at various profile depths are shown in Fig. 7. Except for conventional tillage with initial subsoiling treatment, there was a general decrease in organic carbon levels with increase in depth. The decrease was significantly drastic between 0-30 cm and 30-60 cm but not between 30-60 cm and 60-90 cm. In the 0-30 cm horizon, organic carbon generally decreased in the order: fallow land with sub soiling > fallow land without initial subsoiling > conventional tillage without sub soiling > conservation tillage with initial subsoiling > conservation tillage without initial subsoiling and lastly convectional tillage with initial subsoiling. In the 30-60 cm depth, organic carbon decreased as follows: conventional tillage with initial subsoiling > conservation tillage with initial subsoiling; conventional tillage with no initial subsoiling = conservation tillage with initial subsoiling > fallow land with initial subsoiling and lastly, conservation tillage with initial subsoiling. At 60-90 cm depth, there was a general decrease in organic carbon for all tillage systems and initial subsoiling treatments.

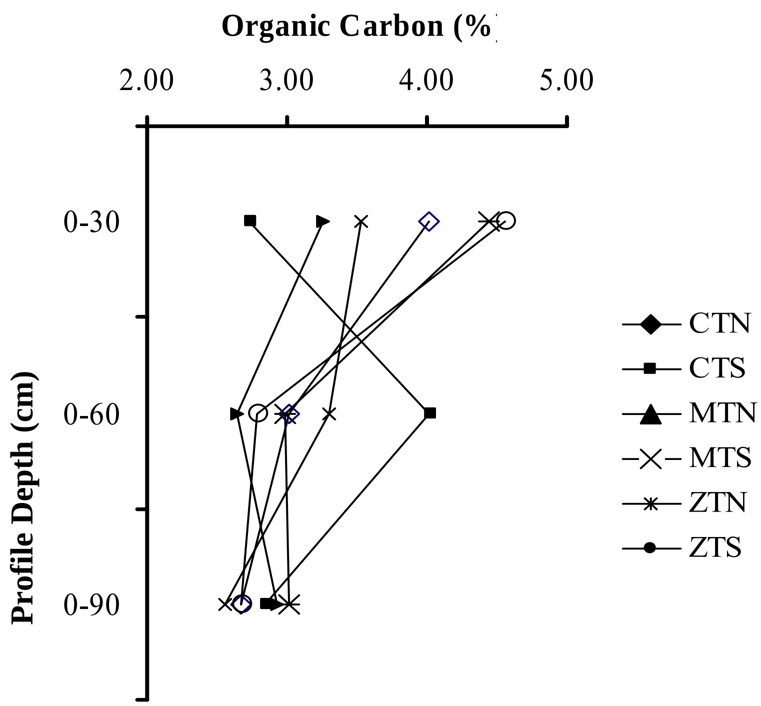

Figure 7: Effect of tillage systems on percent organic carbon at various depths of the profile. CTN: conventional tillage with no initial subsoiling; CTS: conventional tillage with initial subsoiling; MTN: conservation tillage with no initial subsoiling; MTS: conservation tillage with initial subsoiling; ZTN: fallow land with no initial subsoiling; ZTS: fallow land with initial subsoiling.

In the 0-30 cm horizon, high organic carbon in the fallow and conservation tillage treatments was probably due to absence and low levels of disturbances respectively and hence less oxidation of the in situ organic matter. It is also related to higher input of organic matter by grass above ground and root biomass (Pinheiro *et al*., 2004). Dalal, (1989) found out that, high organic carbon content in conservation tillage than in conventional tillage systems was due to reduced mineralization of organic matter in conservation tillage system. Several studies have shown that reduced tillage practices can result in higher stocks of soil organic matter compared with conventional tillage practices (Doran, 1980; Lamb *et al*., 1985; Bruce *et al*., 1990; Havlin *et al*., 1990).

In the 30-60 cm depth conventional tillage had the highest amount of organic carbon unlike in the 0-30 cm depth whereby the same treatment was the least. This increment in organic carbon levels can be attributed to the impact of soil mechanical disturbance especially soil inversion during conventional tillage practices. Initial subsoiling of this horizon led to significantly higher organic carbon content compared to no initial subsoiling treatment (Table 3). This was probably as a result of reduced resistance, enhanced root penetration and probably organic matter enrichment due to the process (Fig 8). This observation indicated that initial subsoiling can be applied to combat the pumice horizon in the same manner Yalcin and Cakir (2006) applied it in severely compacted soils.

Table 2. Organic carbon (%) at different profile depths in different tillage systems

Tillage systems	Organic carbon (%)		
	0-30 cm	30-60 cm	60-90 cm
Fallow	4.49^{a}	2.90^{c}	2.83^{c}
Conservation	3.77^{ab}	2.97^{c}	2.74^{c}
Convectional	3.00^{c}	3.51^{bc}	2.76^{c}

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

Percent organic carbon of the various tillage systems in the different profile depths are shown in Table 2. In the top 0-30 cm horizon of the profile, a significant decrease in organic carbon was observed in convectional tillage compared to the control (fallow land). Conservation tillage was not significantly different from the control (fallow land). There were no significant differences in organic carbon levels in the 30-60 cm horizon for the two tillage systems and the control.

A B

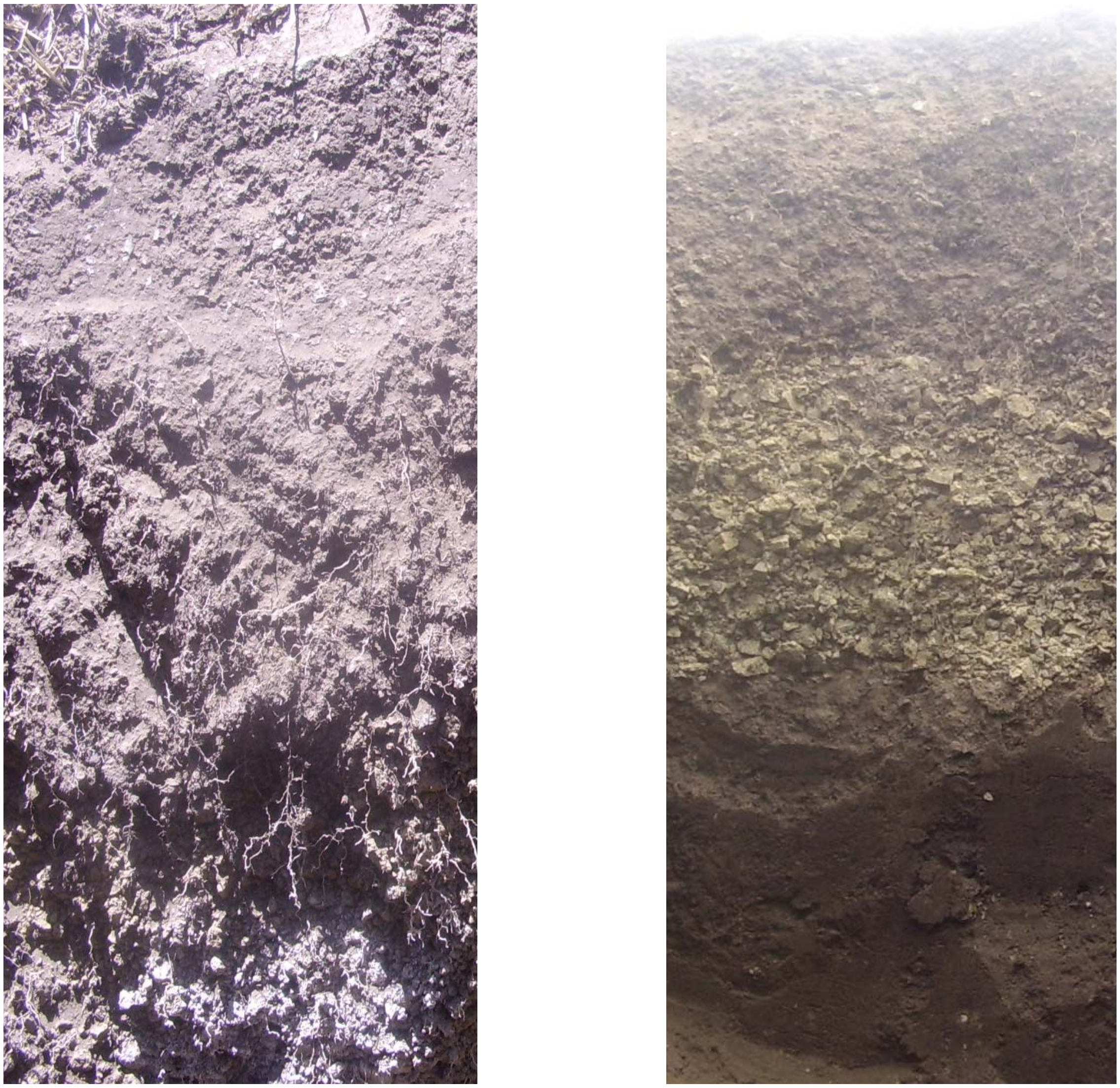

Figure 8: Photographs of vertically oriented profiles showing the effects of initial subsoiling with respect to root penetration; A is a profile where initial subsoiling was applied while B is a profile without initial subsoiling treatment (2006).

Fallow land had the highest average content of organic carbon in the profile followed by conservation and lastly conventional tillage. Conventional tillage reduced organic carbon by about 50% in 0-30 cm horizon; affirming that this tillage system inverted the soil and allowed redistribution and faster mineralization of soil organic matter. This concurs with observations by Castro Filho *et al*., (2002) that conventional tillage system uniformly distributed soil organic carbon in a soil profile. During conventional tillage, the soil is fractured, inverted and opened allowing for faster mineralization of soil organic matter as observed in the 0-30 cm horizon. In the long run, convetional tillage affects not only organic matter distribution in the profile but also the amounts. Conventional tillage is considered to cause acceleration of mineralization of organic matter, loss of nutrients, disruption of soil aggregates exposing more organic matter to microbial attack reduction in the soil fauna and microbes (Beare *et al*., 1994).

The high organic carbon content in the 0-30 cm horizon in conservation tillage system and fallow land might have resulted from high crop residue input and lack of soil disturbance in these tillage systems. This concurs with observations by Castro Filho *et al*. (2002) that, the tendency of soil organic matter in the minimally tilled field is to concentrate near the surface while in conventional tillage system, soil organic carbon is more uniformly distributed. Sa *et al*. (2001) also observed a significant increase in soil organic carbon content in the upper horizon in soils under conservation tillage compared with soil under conventional tillage.

Table 3. Organic carbon (%) at different soil profile depths with and without subsoilig

Profile depth (cm)	With Initial subsoiling	No initial subsoiling
0-30	3.58^{ab}	3.93^{a}
30-60	3.41^{b}	2.84^{c}
60-90	2.67^{c}	2.89^{c}

Values with the same letter superscripts are not significantly different (α = 0.05).

Effect of initial subsoiling on percent organic carbon in various profile depths are shown in Table 3. There was no significant difference between initial subsoiling and no initial subsoiling in the 0-30 cm horizon. Initial subsoiling significantly affected 30-60 cm horizon. Initial subsoiling led to significant increase in organic carbon concentration in the 30-60 cm horizon from 2.48% in no initial subsoiling to 3.41% in initially subsoiled treatments (Table 3). Initial subsoiling of 30-60 cm horizon provided favourable environment for root development (Fig. 8. Compare root density of A and B) due to mechanical breaking of the pumice horizon. Initial subsoiling process probably resulted in enhanced water movement and retention leading to increased organic matter input to this horizon as a result of microbial activities such as root decomposition. It also facilitated root development leading to increased root penetration that led to higher organic matter input. This helps plants withstand short term drought conditions due to easier access to higher amounts of productive moisture accumulated in the subsurface soil especially below the 30-60 cm (pumice horizon). It compares positively with the findings of Yalcin and Cakir, (2006).

Generally the 60-90 cm depth horizon had low value of organic carbon content. Tillage systems, initial subsoiling and no initial subsoiling treatments had no significant effects in this horizon. This observation may be attributed to the minimal disruption of this horizon.

4.2 Aggregate Stability

Percent aggregate size fraction in the various aggregate size classes for the three tillage systems in the top 0-30 cm horizon are shown in Figure 9. In all tillage systems, aggregate distribution were dominated by >2 mm macro aggregates. Fallow land had the highest percent aggregate size fraction in > 2mm class of about 90 %, followed by conservation tillage with approximately 80% and least in conventional tillage with 58%. In conventional tillage, there was a more systematic soil aggregate distribution across several size aggregate classes. This led to higher percent aggregate size fractions in 2-4, 1-2, 0.5-1, 0.18-0.1, 0.063-0.1 mm aggregate size classes compared to fallow and conservation tillage. Unlike in conventional tillage, fallow and conservation tillage had more soil aggregates (more than 80% of the total soil) in the >2 mm aggregate size class. Due to the nature and conditions of 30-60 cm horizon (pumice horizon) it was not possible to determine its aggregate stability.

High MWD in both fallow and conservation tillage was as a result possibly of high organic carbon content (Table 2) in these tillage systems. Salinas-Garcia *et al*. (1997) reported that, in both fallow and conservation tillage, residues accumulate at the surface where the litter decomposition rate is slowed. This is due to drier conditions and reduced contact between soil microorganisms and litter. Aggregate formation can be mechanical, electrostatic or biological in nature. Mechanically, roots in conservation tillage favoured aggregate formation and stabilization directly by physically enmeshing soil particles into aggregates (Hillel 1980b). Other root related processes affecting the soil aggregate are dead root decomposition and root exudation (aggregate cementing agents). As plant roots release organic material within the

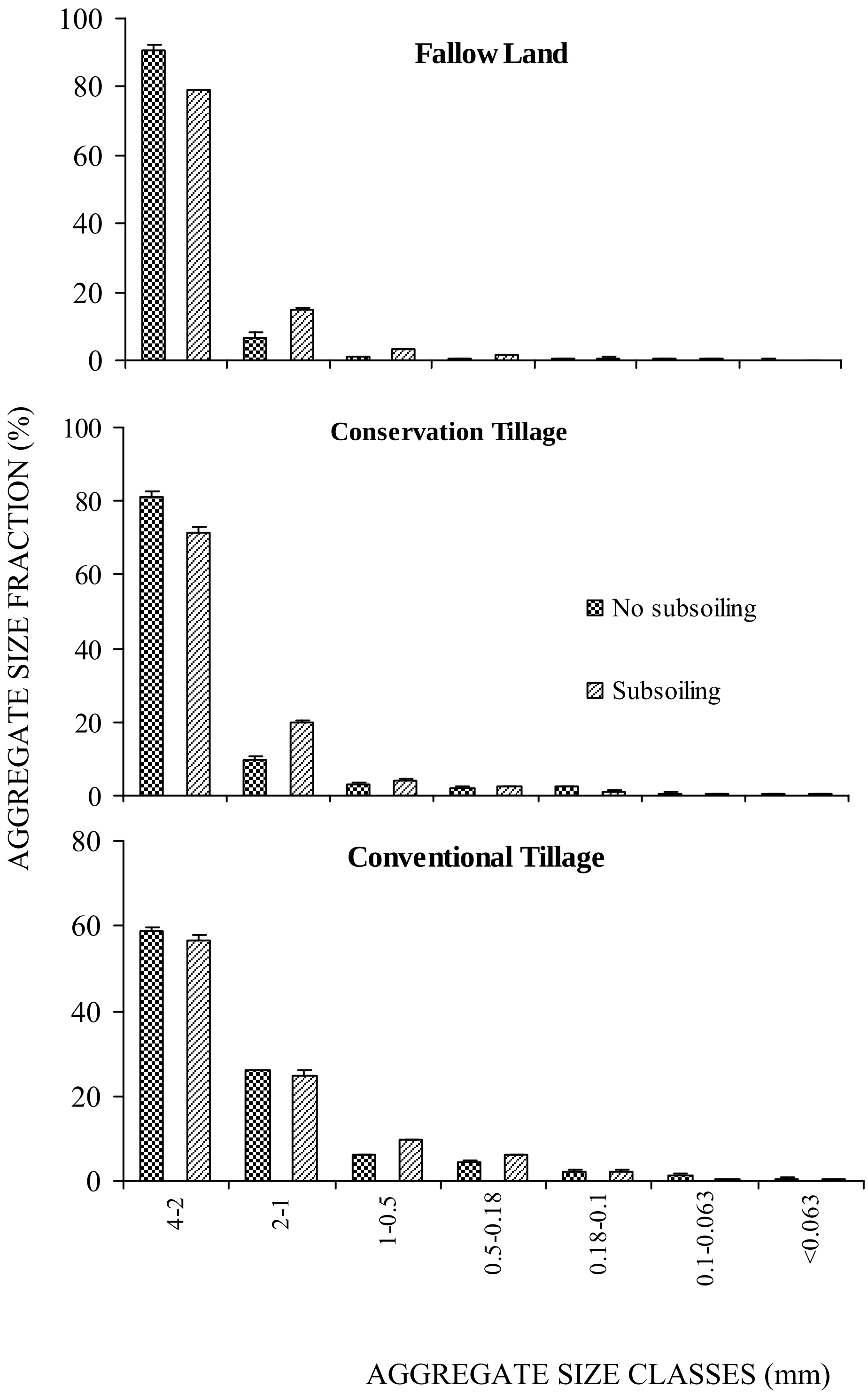

Figure 9: Percent aggregate distribution for the various tillage systems at 0-30 cm horizon. Bars indicate standard deviation.

rhizosphere, they directly and indirectly, through microbial stimulation affect soil structure. Mucilage produced by plant roots bind soil particles together (Caesar-TonThat, 2002). Angers *et al*. (1993) positively correlated the improvement in soil stability with microbial biomass. Plant water uptake by roots causes localized drying of the soil which promotes the binding of root exudates on the clay particles (Ghildyal and Tripathi, 1987).

The more systematic soil aggregate classes observed in conventional tillage were an indication to loss of soil structure. This was attributed to mechanical disruption and exposure of soil organic matter previously preserved to oxidation. It also pulverised soil aggregates into microaggregates hence a reduction in amount of macroaggregates (Tisdall and Oades, 1982). Elliot (1986) reported that, the primary source of organic matter lost during cultivation is the organic matter binding microaggregates into macroaggregates.

The aggregate mean weight diameters for the various tillage systems in 0-30 cm and 60-90 cm horizons are shown in Table 4. In 0-30 cm horizon, significantly lower mean weight diameter was observed in conventional tillage alone. Fallow land and conservation tillage were not significantly different from each other. There were no significant differences in MWD of 60-90 cm horizon between conventional and conservation tillage systems but fallow land was significantly higher than both.

Table 4. Mean weight diameter under various tillage systems and profile depths

Tillage systems	Mean weight		
	0-30 cm	30-60 cm	60-90 cm
Fallow	2.61^{a}	-	2.43^{b}
Conservation	2.60^{a}	-	2.16^{c}
Convectional	2.22^{c}	-	2.16^{c}

Values with the same letter superscripts are not significantly different (α = 0.05).

The high and non significant mean weight diameter in both fallow and conservation tillage related directly to high carbon content in the same tillage systems as observed in Table 2.

Likewise, conventional tillage had significantly lower mean weight and organic carbon levels (Tables 4 and 2 respectively) in 0-30 cm horizon. These observations are in agreement with Puget *et al*. (1995) and Jastro *et al*. (1996) who observed increasing proportions of aggregate sizes with increasing carbon content.

Fallow and conservation tillage systems led to significant increase in organic carbon content and hence significantly higher soil aggregate formation. The frequent reporting of improvements of soil structure under conservation tillage is mostly attributed to increases in organic matter content (Chan *et al*., 2002). Crop residue mulch and high organic matter input has been reported to improve soil quality in terms of organic carbon and hence higher microbial activities (Karlen *et al*., 1994; Lal, 1989). Majority of biologically formed bonds that bind soil particles into aggregates are caused by micro organisms. Organic residues form the nucleation centre for aggregate formation through production of microbial derived substances such as polysaccharide gums that bind residue and soil particles into aggregates. Consequently, enhanced microbial activity through organic matter input in fallow and conservation tillage must have stimulated aggregate formation. Electrostatically, organic matter is very important as the primary binding agent for soil aggregates especially in moderately weathered soils such as vitric Andosols. These soils are dominated by 2:1 clay minerals, where the negative surface charges of soil organic matter and clay minerals are mutually bound to positively charged polyvalent metal cations.

Table 5. Initial subsoiling and no initial subsoiling effect on mean weight diameters of the different tillage systems.

Tillage systems	MWD	
	With initial subsoiling	No initial subsoiling
Fallow	2.30^{c}	2.73^{a}
Conservation	2.21^{cd}	2.55^{b}
Conventional	2.15^{d}	2.19^{cd}

Values with the same letter superscripts are not significantly different (α = 0.05).

The aggregate mean weight diameter with and without initial subsoiling sub-factors on the tillage systems and profile depth are shown in Table 5.

Initial subsoiling significantly reduced MWD in conventional tillage alone compared to the control (fallow land) (Table 5). In no initial subsoiling treatment, there were significant differences between all the three tillage systems. Fallow land had the highest MWD followed by conservation tillage while conventional tillage had the least. Except for conventional tillage, there was significant difference in conservation tillage and fallow land between initial subsoiling and no initial subsoiling treatments (Table 5). Both in fallow land and conservation tillage systems, initial subsoiling led to significant reduction in their mean weight diameters. These differences in aggregate stability were probably as a result of differences in the extend of soil mechanical disruption and organic matter contents. Initial subsoiling contributed to soil structure loss through aggregate breakdown.

4.3 Bulk Density

The effects of various tillage systems and initial subsoiling on bulk density at various profile depths is shown in Fig. 10. There was a decrease in bulk density of all tillage systems with increase in depth from 0-30 cm horizon to 30-60 cm horizon. From 30-60 cm to 60-90 cm horizon, there was a general increase in bulk densities for all the treatments. Within, 0-30 cm horizon, it was observed that conservation tillage with no subsoiling had the highest bulk density followed by fallow land with no subsoiling > conservation tillage with initial subsoiling > fallow land with initial subsoiling > conventional tillage with initial subsoiling and lastly conventional with no initial subsoiling.

The trend observed in Fig. 10 that the bulk density was higher in 0-30 cm, then decreased in the 30-60 cm and finally increased in the 60-90 cm depth can be attributed to the nature and composition of each soil horizon under consideration. The top 30 cm of the profile was mainly composed of mineral soils with various amounts of organic matter. The low bulk densities of the conventional tillage treatment in the 0-30 cm depth reflect the loosening effect of this tillage treatment. One of the goals of tillage, especially conventional tillage, is to reduce bulk density and hence increase soil porosity (Hillel 1980b). This effect of tillage on bulk density is temporary, and after tillage, soil rapidly settles, recovering its former bulk density. Elimination of soil mechanical loosening caused by tillage operations in conservation tillage system was most probably responsible for the increase in soil bulk density in 0-30 cm depth. Also, soil bulk density might have increased due to repeated passes of field machines during field operation under conservation tillage, the soil might have been in the transition or repair period in which it builds humus, regains its structural stability and restores the pore space (Kinsella 1995). During this period, there is first an increase in bulk density and then a decrease due to restructuring process, until an equilibrium level is reached when the structure is fully restored. The low bulk density of 30-60 cm depth horizon was due to its morphological nature and composition. This horizon was composed mainly of a thick layer of porous, permeable, fine grained volcanic ash material (pumice rock). Pumice rock is the parent rock for Andosol soils (FAO 2003). The 60-90 cm horizon was composed of well developed mineral soil that was probably buried due to volcanic activities.

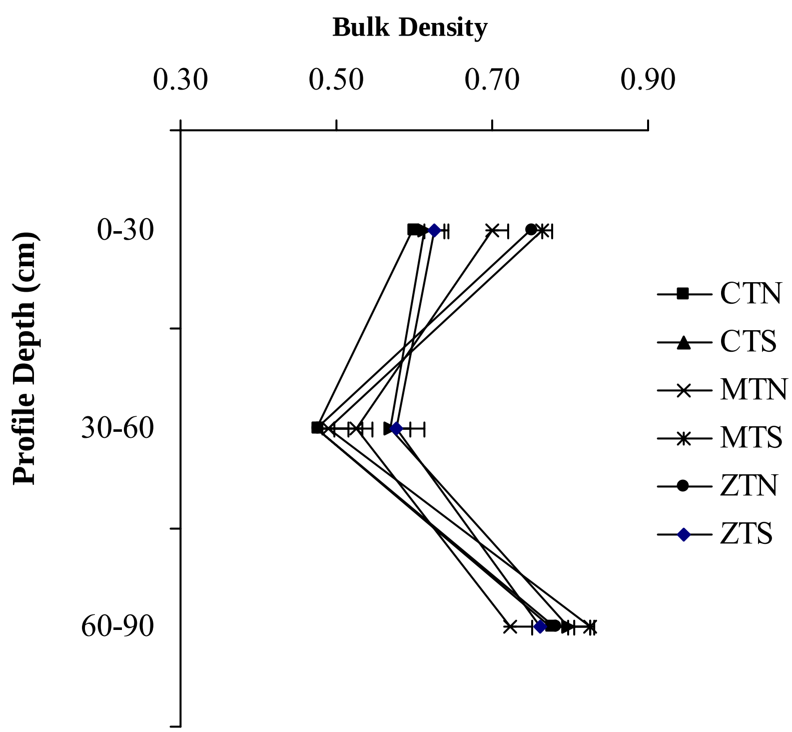

Figure 10: Effects of tillage systems and initial subsoiling treatments on bulk density (Mg/M^3) at various depths of the profile. CTN: conventional tillage with no initial subsoiling; CTS: conventional tillage with initial subsoiling; MTN: conservation tillage with no initial subsoiling; MTS: conservation tillage with initial subsoiling; ZTN: fallow land with no initial subsoiling; ZTS: fallow land with initial subsoiling. Bars indicate standard deviation.

Bulk densities for various tillage systems and profile depths are shown in Table 6. In 0-30 cm horizon, bulk densities were significantly different between all the tillage systems. In conventional tillage, bulk density was significantly low while in conservation tillage system it was significantly high compared to fallow land (control). There were significant differences of bulk densities in the three profile depths in each tillage system. On average, 60-90 cm horizon had the highest bulk density intermediate in 0-30 cm and least in the 30-60 cm horizon. There were no significant differences in tillage systems within 30-60 cm and 60-90 cm horizons for the three tillage systems. The low bulk density of the top 0-30 cm compared to 60-90 cm horizon can be attributed to its genesis. This horizon of the profile might have developed as a new profile horizon from the fresh volcanic ash (pumice horizon). According to FAO (2003), the surface horizon of an Andosol is generally very porous, very friable and has crumb or granular structure with average organic matter of 8 to 30 %. This might explain the average low bulk density of 0-30 cm horizon as compared to 60-90 cm depth. Furthermore crop residue/mulch improve soil quality in terms of organic carbon and biotic activity (FAO 2003). Generally, organic carbon have low density hence when incorporated into soil tends to lower its bulk density. This might be the cause for lower bulk density, particularly in the 0-30 cm horizon in the fallow land treatment.

Table 6. Bulk densities for the different tillage systems in different profile depths.

Tillage systems	Bulk density		
	0-30 cm	30-60 cm	60-90 cm
Fallow	0.69^{c}	0.53^{e}	0.77^{ab}
Conservation	0.73^{b}	0.51^{e}	0.78^{a}
Convectional	0.61^{d}	0.52^{e}	0.79^{a}

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

The significantly high (0.78 Mg/M^3) bulk density of 60-90 cm depth was attributed to the genesis and development process of the whole profile. By observing the profile, there was an apparent indication that there was a deposition of a thick layer of ash (pumice horizon). The 60-90 cm horizon depicts a well developed and old horizon composed of mineral soil.

Initial subsoiling and no initial subsoiling effects on bulk densities of soils under various tillage systems shown in Table 7. No significant differences were observed in initial subsoiling treatments between all the three tillage systems. In the no initial subsoiling treatment, conventional tillage was significantly different from both fallow and conservation tillage. Conventional tillage had significantly low bulk density (0.62 Mg/M^3) in no initial subsoiling treatment. This was attributed to loosening and pulverization effect of this tillage system on the soil (Hillel 1980b).

No initial subsoiling treatments were significantly different from initial subsoiling in conservation and conventional tillage except in fallow land treatment. Initial subsoiling led to significantly lower bulk density in conservation tillage from 0.69 to 0.65 Mg/M^3, while in conventional tillage; it resulted to significant increase in bulk density from 0.62 to 0.66 Mg/M^3. The mechanical breaking/loosening effect of initial subsoiling on the pumice horizon must have led to homogenization/mixing of pumice horizon (0-30 cm) which naturally had low bulk density with the top horizon. Its effect being reduction in bulk density of 0-30 cm horizon.

Table 7. Initial subsoiling and no initial subsoiling effects on bulk densities (Mg/M^3) of the different tillage systems

Tillage system	Bulk density	
	With initial subsoiling	No initial subsoiling
Fallow	0.65^{b}	0.67^{ab}
Conservation	0.65^{b}	0.69^{a}
Conventional	0.66^{b}	0.62^{c}

Values with the same letter superscripts are not significantly different (α = 0.05).

Initial subsoiling had significant effect in all the three horizons (Table 8). In the 0-30 cm soil depth, initial subsoiling treatment was significantly lower (0.65 Mg/M^3) from no-initial subsoiling. In 30-60 cm horizon, initial subsoiling led to significantly higher bulk density (0.56Mg/M^3) compared to no initial subsoiling. In the 60-90 cm depth, initial subsoiling had significantly lower bulk density (0.76 Mg/M^3). The low bulk density in 0-30 cm depth can be attributed to soil mechanical disruption increase in the amount of pumice particles due to homogenising effect of initial subsoiling process. High bulk density in initial subsoiling of 30-60 cm horizon was mainly due to its mechanical breaking/loosening effect.

Initial subsoiling led to homogenization/mixing of both the plough layer (0-30 cm horizon) and the 60-90 cm mineral soil with 30-60 cm pumice horizon. Due to the high particle density of the mineral soil over the pumice particles, the mixing of the two led to an increase in overall bulk density of 30-60 cm horizon.

Table 8. Initial subsoiling and no initial subsoiling effects on bulk densities (Mg/M^3) of the at different profile horizons

Depth (cm)	Bulk density	
	With initial subsoiling	No initial subsoiling
0-30	0.65^d	0.70^c
30-60	0.56^e	0.48^f
60-90	0.76^b	0.79^a

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

4.4 Hydraulic Conductivity

Tillage systems effects on the hydraulic properties of the soil are shown in Table 9. There were significant differences in infiltration rates of the different tillage systems in 0-30 and 30-60 cm horizons. There were no significant differences between the different tillage systems in 60-90 cm horizon. In 0-30 cm horizon, hydraulic conductivity was significantly lower in both conventional tillage (0.90 cm/hr) and conservation tillage (0.76 cm/hr) compared to the control (fallow land) (1.59 cm hr^{-1}). The high hydraulic conductivity of the conventional tillage treatment compared to conservation tillage can be attributed to the low bulk density of this treatment (Table 6) and hence the conductivity due to a lager or greater number of voids and cracks caused by tillage implements. Bulk density is inversely related to porosity (Carter and Ball 1993), which gives an idea of the porous space left in the soil for air and water movement. High bulk density (low porosity) reduces water movement and increases penetration resistance, limiting root growth (Cassel 1982). The generally high hydraulic conductivity of the control (fallow land) suggests greater pore continuity. The same observation was made by Sharrat *et al*., (2006) and Mahboubi *et al*., (1993) that, more than 20 years of establishing tillage treatments, conservation tillage resulted in a higher hydraulic conductivity compared with conventional tillage. Schwartz *et al*., (2003) explained that, higher hydraulic conductivities for grassland, was due to shrink-swell cycles and/or biological activity giving rise to development of less tortuous and more continuous pores under native grassland. It is likely that, apart from macropore variations, high hydraulic conductivity was caused by better continuity, less tortuosity and greater number of preferential flow channels.

Table 9. Tillage system effect on hydraulic conductivity (cm/hr) of the three profile horizons.

Tillage systems	Hydraulic conductivity		
	0-30 cm	30-60 cm	60-90 cm
Fallow	1.59[c]	1.70[c]	0.45[e]
Conservation	0.76[e]	2.41[a]	0.52[e]
Convectional	0.90[d]	2.04[b]	0.56[e]

Values with the same letter superscripts are not significantly different (α = 0.05).

The 30-60 cm horizon had the highest hydraulic conductivity compared to 0-30 cm and 60-90 cm horizons. The trend related inversely with the bulk densities of this horizons (Table 8). This observation can be attributed to the physical nature and composition of each horizon. The high hydraulic conductivities of 30-60 cm horizon (Table 10) was probably due to the low bulk densities and hence high porosity and permeability of this horizon (Fig. 10). The hydraulic conductivity of this horizon related negatively with its bulk density. This horizon had lowest bulk density compared to 0-30 cm and 60-90 cm horizons (Table 8). And since bulk density relates inversely with porosity (Carter and Ball 1993), the observation can be explained by applying the Poiseuilles law (Ghildyal and Tripathi, 1987);

$$q = \frac{\pi r^4}{8\eta}\left(\frac{\Delta P}{L}\right) \qquad (18)$$

Where q is volume flow rate, in cm^3 sec^{-1} r is radius of the pore, cm, η is coefficient of viscosity of liquid in dyne-sec cm^{-2}, P is pressure dynes, cm^{-2} and L is the pore/tube length in cm.

From equation 18, the flow velocity is related to the radius of the circular capillaries in the order of fourth power. It follows then that, if the size of the channel is increased by half, then, the conductivity is increased by 1/16. Therefore, the low bulk density (high porosity hence increase in size) of 30–60 cm horizon is likely to be the reason for high hydraulic conductivity in accordance with Poiseuilles law. Also the low hydraulic conductivity for the 60-90 cm horizon was probably due to high bulk density hence low porosity of this profile depth compared to 30-60 cm depth horizon.

Initial subsoiling effects on hydraulic conductivity of different tillage systems are shown in Table 10. There were no significant differences on the effect of initial subsoiling on hydraulic conductivities under various tillage systems.

Initial subsoiling effects on hydraulic conductivity of the three profile horizons are shown in Table 10. Except for the 60-90 cm horizon, there were significant differences in hydraulic conductivity due to initial subsoiling. In 0-30 cm depth, initial subsoiling led to a significantly high hydraulic conductivity (from 0.79 to 1.20 cm/hr).

Table 10. Initial subsoiling effects on hydraulic conductivities (cm/hr) of tillage

Tillage systems	Hydraulic conductivity	
	With initial subsoiling	No initial subsoiling
Fallow	1.27^{a}	1.22^{a}
Conservation	1.16^{a}	1.30^{a}
Conventional	1.13^{a}	1.21^{a}

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

In 30-60 cm horizon, initial subsoiling treatment caused a significant reduction in hydraulic conductivity from 2.19 to 1.90 cm/hr. There was no significant impact in 60-90 cm horizon whether it was subsoiled or not. Generally, the three horizons under consideration differed significantly with 30-60 cm depth having the highest average hydraulic conductivity followed by 0-30 cm depth while 60-90 cm depth was the lowest.

Table 11. Initial subsoiling effects on hydraulic conductivities (cm/hr) of the three horizons

Depth (cm)	Hydraulic conductivity (cm/hr)	
	With initial subsoiling	No initial subsoiling
0-30	1.20^{c}	0.79^{d}
30-60	1.90^{b}	2.19^{a}
60-90	0.54^{e}	0.48^{e}

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

The effect of initial subsoiling on bulk density of the profile related strongly in an inverse manner with the effect of initial subsoiling on the hydraulic conductivity of the various horizons as shown in Table 8 and 11 respectively. The significant increase in 0-30cm depth due to initial subsoiling must have been as a result of low bulk density of 0.65 Mg/M^3 (hence high porosity) (Table 8) due to loosening and mixing effect of initial subsoiling. The significant reduction of hydraulic conductivity in 30-60 cm depth as a result of initial subsoiling was attributed to disturbance and mixing of this horizon with the top 0-30 cm and bottom 60-90 cm minerals soils. The mixing resulted in high bulk density. According to Poiseuilles law (Equation 18); the size of conductivity channels must have reduced considerably and hence the reason for decrease in hydraulic conductivity. The organic carbon levels were also high in the same treatment (Table 2). The relatively higher organic carbon levels might have boosted flourishing of microbial activities within this horizon. Marschner *et al*., (2003) reported that microbial community structure is correlated to soil organic carbon. Decomposition of organic residues leading to higher turnover of metabolic products such as slimes gums and gases that clogged capillary pores (Ghildyal and Tripathi, 1987) might have contributed to the low hydraulic conductivity.

4.5 Infiltration Rate

Infiltration rates for three tillage systems with and without initial subsoiling treatments are shown in Fig. 11. From 0-30 to 30-60 cm horizon, there was a decrease in infiltration rate of fallow land with no initial subsoiling, fallow land with initial subsoiling and conventional tillage with initial subsoiling systems while conservation tillage with initial subsoiling, conservation tillage with no initial subsoiling and conventional tillage with no initial subsoiling increased. From 30-60 cm horizon to 60-90 cm horizon, there was a general decrease in infiltration rate for all the treatments. In 0-30 cm horizon, the treatments separated into two infiltration rate groups. Fallow land without initial subsoiling, fallow land with initial subsoiling and conventional tillage with initial subsoiling were in one group. The other group was made up of conservation tillage without initial subsoiling, conservation tillage with initial subsoiling and conventional tillage with initial subsoiling.

The relatively high infiltration rate of the control (fallow land) with and without initial subsoiling was probably due to greater macroporosity or pore continuity in the 0-30 cm depth (*Schwartz et al*., 2003). It has been observed by Mazurak and Ramig, (1962); Kay, (1990) that, perennial grasses, effect changes in soil hydraulic properties over time. This results from root activity, the development of biopores, improved aggregate stability resulting from greater carbon sequestration (Unger, 2001), and enhanced wetting-drying cycles mediated by extraction of water by perennial grasses. It also related positively with organic carbon levels of these particular treatments within the same profile depth (Table 2). The high organic carbon levels must have favoured population growth of microorganisms, especially bacteria, fungi and actinomycetes. Fungi and actinomycetes ramify and produce considerable amounts of mycelia which help to mechanically bind aggregates (Ghildyal and Tripathi, 1987). Bacteria may cement the particles with cementing (gum) agents they produce. Microbial synthesis of soil cementing agents like polysaccharides is one of the factors in aggregate stabilization (Caesar-TonThat, 2002). However the effect is due to decomposition of mycelia and products of microbial synthesis (Ghildyal and Tripathi, 1987). The products of microbial decomposition like aminoplyurronides, proteins and lignin like colloidal materials, fats, resins and waxes have cementing effect (Pierson and Mulla, 1990; Smettem *et al*., 1992). They play a major role in formation and stabilization of soil aggregates (Caesar-TonThat, 2002). Well granulated and stable solid aggregates favoured high infiltration rates and hence the observation in the fallow land treatments.

Conventional tillage with initial subsoiling ranked higher than conservation tillage system whether subsoiled or not. This might be due to the mixing effect of initial subsoiling leading to loosening and incorporation of the pumice particle from 30–60 cm depth. The cumulative effect of incorporation of pumice particles into 0-30 cm horizon led to higher infiltration rates. This was due physical and hydraulic properties of pumice as observed in hydraulic conductivity, bulk density, organic carbon and texture results. The low infiltration rates of conventional tillage with no initial subsoiling were probably due to the intensity of cultivation. Intensive tillage practices and pulverization of soil exposes soil organic matter to aeration and thus mineralization (Cannell and Hawes, 1994). While the process leads to reduced potential biological and biochemical activity (Doran *et al*., 1998; Riffaldi *et al*., 2002), the main problem is aggregate destruction (Golchin *et al*., 1994; Bossuyt *et al*., 2002; Plante and McGill, 2002; Achmed *et al*., 2003) leading to decrease in stability, number and continuity of preferential flow channels or macropores due to soil pulverisation.

In the 30–60 cm depth, the trend in infiltration rate changed compared to the 0-30 cm horizon as observed in Fig. 11. Conventional tillage with no initial subsoiling had the highest infiltration rate followed by fallow land with no initial subsoiling; conservation tillage with no initial subsoiling; fallow land with initial subsoiling and lastly conventional tillage with initial subsoiling. Note the striking relationship of the first three; they are all the three tillage systems with no initial subsoiling sub-factor. Lack of initial subsoiling of this horizon seemed to favour high infiltration rates due to its nature and composition. The 30-60 cm horizon had low bulk density (high porosity) (Table 8) and was composed of thick layer of porous, permeable, fine grained volcanic ash. These physical properties favoured the downward movement of water due to low resistance to water conductivity.

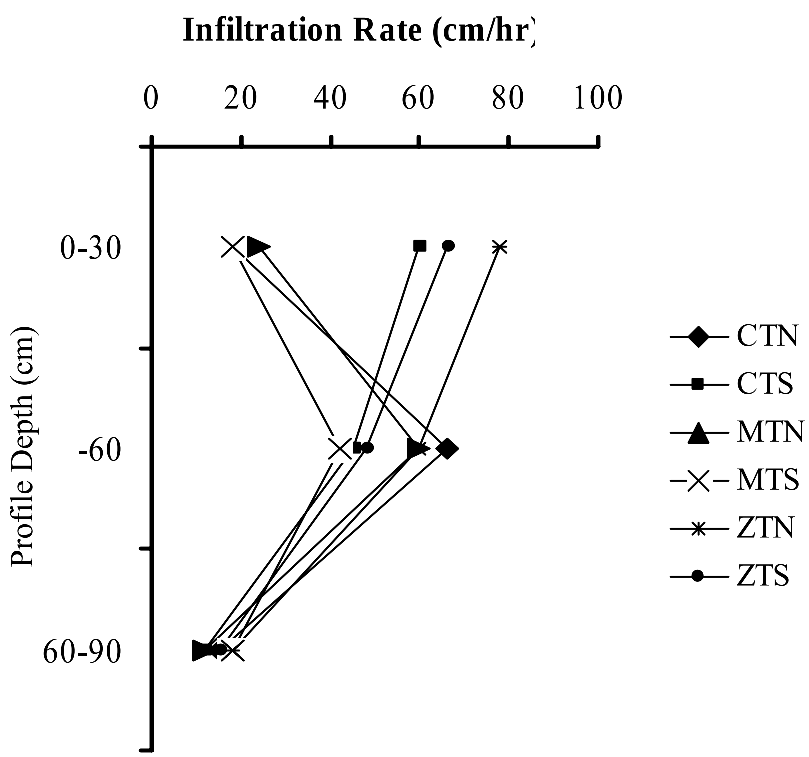

Figure 11. Effects of tillage and initial subsoiling treatments on infiltration rate at various depths of the profile. CTN: conventional tillage with no initial subsoiling; CTS: conventional tillage with initial subsoiling; MTN: conservation tillage with no initial subsoiling; MTS: conservation tillage with initial subsoiling; ZTN: fallow land with no initial subsoiling; ZTS: fallow land with initial subsoiling.

The high infiltration rates of no initial subsoiling in the 30-60cm depth were probably due to the physical properties of pumice horizon. In such a scenario, as water flows vertically downwards, it is temporarily impeded at the 30 cm depth interface. This is due to the too high suction of the 0-30 cm depth mineral soil to allow the entry of water into the limiting coarse pumice horizon. The pumice horizon limits the flow because of its macropores that are too large to take water from the micropores. The downward movement may temporarily stop until when the surface horizon is almost saturated. Water will enter the pumice horizon only when the suction is reduced to the value determined by the size of pores in the coarse pumice horizon at the interface as defined by Equation 19 (Ghildyal and Tripathi, 1987). It shows that suction is inversely related to the pore radius/size.

$$\tau = \frac{2\gamma}{r} \qquad (19)$$

where τ is soil water suction in dyne-cm, γ is surface tension and r is the pore radius.

Once the suction in the 30cm interface is low enough, water will move into and through it rapidly. However, in the 60 cm interface, since the downward movement of water in the fine mineral layer will be appreciably reduced. The flow rate reduction was attributed to the presence of fine pores, which offer a higher resistance to water passage. The soil suction in the coarse pumice horizon will remain low compared to fine mineral soil of the 0-30 cm and 60-90 cm depths that led to reduction in porosity (high bulk density) as shown in Table 8.

Infiltration rates reduced drastically in all the treatments in 60-90 cm depth of the profile. All treatments had almost equal values of 15 cm/hr on average. The average bulk density of this horizon was significantly higher compared to 0-30 cm and 30-60 cm depth horizons (Table 8). The high bulk density and hence low porosity led to higher resistance to water passage due to reduced macropores. This was probably due to relatively minimal interferences/disturbance.

The effect of the different tillage systems, initial subsoiling and no initial subsoiling on infiltration rates are shown in Table 12. There were significant differences in infiltration rates of the different tillage systems. Conservation tillage had significantly low (33.0 cm/hr) average infiltration rates compared to the control, while conventional tillage was intermediate (34.5 cm/hr). Conservation tillage favour organic matter accumulation unlike conventional tillage system. The low infiltration rate of this treatment can be attributed to high organic matter. Incorporation of organic matter into the soil when temperature and water conditions are favourable can lead to rapid rise in population of bacteria, fungi and actinomycetes. These microorganisms use the plant residues as source of energy (Marschner *et al*., 2003). A large increase in the population of microorganisms produces intense microbial activities. The degradation products accumulate in the soil and large amounts of organic material of micro organic origin are synthesized **(**Ghildyal and Tripathi, 1987). These microbial products such as slime and gum clog capillary pores and hence might have led to decrease in infiltration rates of the conservation tillage.

Table 12. The effect of initial subsoiling and no initial subsoiling on infiltration rates (cm/hr) of three horizons.

Initial subsoiling	Infiltration rate		
	0-30 cm	30-60 cm	60-90 cm
No initial subsoiling	40.5^{ab}	56.5^{a}	15.5^{c}
With initial subsoiling	47.5^{ab}	50.5^{a}	14.5^{c}

Values with the same letter superscripts are not significantly different ($\alpha = 0.05$).

The effects of initial subsoiling on infiltration rate of the different profile horizons are shown in Table 12. Initial subsoiling effect on profile horizons showed no significant difference within the 0-30 cm and 30-60 cm horizons. There were also no significant differences between the two horizons. Infiltration rates of both 0-30 cm and 30-60 cm horizons were on average significantly higher than that of 60-90 cm horizon. There was no significant difference between initial subsoiling and no initial subsoiling in the 60-90 cm horizon.

From afore analyses, it was observed that, the three horizons in the soil profile had varying thickness with different physical and hydraulic properties. These simple observations of the physical properties of a soil profile with distinct horizons can have great effects in water movement down a profile under field conditions.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Conventional tillage caused 9.4% loss of soil organic carbon than conservation tillage. Carbon content was significantly lower in conventional tillage treatment than in conservation tillage system. Conventional tillage reduced the aggregate stability reduced by 32% compared to fallow land. It reduced the proportion of soil in the 2-4 mm size class. Conventional tillage had the low percent aggregate size fraction in > 2mm class of about 58 %, followed by conservation tillage with approximately 80% and fallow land had the highest with 90%. The aggregate stability (MWD) results showed that conventional tillage induced a greater modification of 0-30 cm depth soil physical properties. Compared to conservation tillage (1.24 cm/hr), conventional tillage had significantly lower (1.7 cm/hr) hydraulic conductivity and infiltration rates of vitric Andosols. Organic carbon content decreased with soil depth in all tillage systems. The decrease was significantly drastic between 0-30 cm and 30-60 cm horizon but not between 30-60 cm and 60-90 cm.

The pumice horizon (30-60 cm) of the initially sub-soiled treatments had significantly high organic carbon content (3.41%) compared to none initially sub-soiled treatments (2.48%). Initial subsoiling increased organic carbon by 37.5%. Initial subsoiling significantly increased hydraulic conductivity of 0-30 cm horizon by approximately 34 % reduced while in 30-60 cm horizon it reduce by 13% (from 2.19 to 1.90 cm/hr) compared to treatment without initial subsoiling. On bulk density, initial subsoiling led to significant reduction in bulk densities of 0-30 cm (from 0.70 to 0.65 Mg/M^3) and 60-90 cm (from 0.79 to 0.76 Mg/M^3) while in 30-60 cm horizon, it resulted to a significant increase. The increase in bulk density of 30-60 cm horizon was due to breaking and pulverising effect of initial subsoiling on the pumice horizon. It resulted in reduced hydraulic conductivity and infiltration rates. It is apparent that initial subsoiling can be applied to break the pumice horizon. It reduced its resistance and provided an increased root depth and enhanced water movement though the profile.

Under field conditions, more often than not, the flow of water through the profile is unsaturated flow. The soil profile under study consisted of pumice horizon sandwiched by, 0-30 cm and 60-90 cm horizons of fine mineral soil leading to various hydraulic gradients at the interfaces of the horizons with varying hydraulic and physical properties. The high hydraulic conductivity of 30-60 cm horizon was attributed to its physical properties. It had low bulk density and was composed of thick horizon of porous, permeable, fine-grained volcanic ash. Due to its unique physical properties, its presence in the profile affects water movement. The pumice horizon impede flow due to its retarding effect on the wetting front (where unsaturated conditions prevail) owing to the lower unsaturated conductivity of the pumice horizon at equal matric potential with the top cultivated horizon. The low hydraulic conductivity (0.51 Mg/M^3) of 60-90 cm horizon was as a result of its high bulk density and hence low porosity.

The results indicate that the different horizons had varying influence on the selected physical and hydraulic properties. The 30-60 cm pumice horizon had unique qualities. It had low organic carbon; low bulk density; high hydraulic conductivity and high infiltration rates. These properties do not favour soil water movement and retention. Hence it was concluded that, 30-60 cm horizon (pumice) in a stratified vitric Andosol is the horizon that most limit soil water movement. The main reason was attributed to suction differences at the 30 cm and 60 cm depth interfaces and hence the effect on wetting front while conventional tillage had the most negative effect on soil physical and hydraulic properties.

5.2 Recommendations

Between conventional and conservation tillage systems, it is recommended that conservation tillage be adopted. For soil stratification, it is recommended that subsoiling be applied as a remedial treatment of 30-60 cm horizon. It breaks the pumice horizon leading to improved soil water movement and retention. This will also enhance plant root development. A combination of initial sub-soiling followed by conservation tillage was the best way to improve the soil physical and hydraulic properties in a stratified vitric Andosols.

It is further recommended that more work should be done to quantify the relationship between profile stratification and water holding capacity of stratified vitric Andosol. Further investigations concerning the practicality and the economics of applying subsoiling in order to improve the hydraulic properties of the pumice horizon should be carried out.

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APPENDICES

APPENDIX 1: RAW DATA

1.1 Organic Carbon

Soil depth	Tillage	Subsoiling	No Subsoiling
0-30	Fallow	4.55	4.44
	Conservation	3.53	4.01
	Conventional	2.73	3.26
30-60	Fallow	3.01	2.79
	Conservation	3.30	2.64
	Conventional	4.01	3.01
60-90	Fallow	2.67	2.99
	Conservation	2.56	2.93
	Conventional	2.84	2.67

1.2 Aggregate Stability (mean weight diameter MWD)

Soil depth	Aggregate Stability		Rep1	Rep 2	Rep 3	Mean
0-30	Fallow	No Subsoiling	2.86	2.81	2.83	2.84
		Subsoiling	2.32	2.38	2.44	2.38
	Conservation	No Subsoiling	2.58	2.65	2.61	2.61
		Subsoiling	2.66	2.52	2.59	2.59
	Conventional	No Subsoiling	2.23	2.25	2.20	2.23
		Subsoiling	2.21	2.21	2.22	2.21
60-90	Fallow	No Subsoiling	2.63	2.64	2.63	2.63
		Subsoiling	2.30	2.23	2.15	2.23
	Conservation	No Subsoiling	2.52	2.49	2.45	2.49
		Subsoiling	1.82	1.85	1.80	1.82
	Conventional	No Subsoiling	2.16	2.13	2.19	2.16
		Subsoiling	2.06	2.09	2.13	2.09

1.2.1 Aggregate Stability Distribution (sieve distribution)

Sample	2 mm	1 mm	0.5 mm	0.18 mm	0.10 mm	0.063mm	>0.063 mm	Total
Conservation tillage+no-subsoiling 1A	3.96	0.54	0.18	0.13	0.13	0.05	0.02	5.00
Conservation tillage+no-subsoiling 2A	4.14	0.45	0.14	0.10	0.12	0.02	0.02	5.00
Conservation tillage+no-subsoiling 3A	4.05	0.50	0.16	0.11	0.12	0.04	0.02	5.00
Conservation tillage+no-subsoiling 1C	3.64	1.01	0.19	0.11	0.02	0.01	0.01	5.00
Conservation tillage+no-subsoiling 2C	3.57	1.00	0.22	0.12	0.05	0.02	0.02	5.00
Conservation tillage+no-subsoiling 3C	3.51	1.00	0.24	0.14	0.07	0.03	0.02	5.00
Conservation tillage+subsoiling 1A	4.06	0.65	0.16	0.07	0.04	0.02	0.00	5.00
Conservation tillage+subsoiling 2A	3.71	0.84	0.20	0.11	0.07	0.05	0.02	5.00
Conservation tillage+subsoiling 3A	3.89	0.74	0.18	0.09	0.06	0.03	0.01	5.00
Conservation tillage+subsoiling 1C	2.23	1.15	0.59	0.63	0.31	0.06	0.03	5.01
Conservation tillage+subsoiling 2C	2.25	1.19	0.60	0.60	0.27	0.07	0.03	5.00

Conservation tillage+subsoiling 2C	2.20	1.11	0.59	0.65	0.35	0.06	0.04	5.00
Conventional tillage+no-subsoiling 1A	2.95	1.31	0.30	0.22	0.12	0.06	0.03	5.00
Conventional tillage+no-subsoiling 2A	2.99	1.31	0.32	0.20	0.10	0.05	0.03	5.00
Conventional tillage+no-subsoiling 3A	2.91	1.30	0.29	0.25	0.14	0.08	0.03	5.00
Conventional tillage+no-subsoiling 1C	2.82	1.23	0.48	0.32	0.12	0.02	0.01	5.00
Conventional tillage+no-subsoiling 2C	2.74	1.30	0.48	0.31	0.14	0.02	0.01	5.00
Conventional tillage+no-subsoiling 3C	2.90	1.16	0.48	0.32	0.10	0.02	0.01	5.00
Conventional tillage+subsoiling 1A	2.93	1.31	0.26	0.21	0.16	0.08	0.04	5.00
Conventional tillage+subsoiling 2A	2.89	1.38	0.27	0.20	0.15	0.07	0.04	5.00
Conventional tillage+subsoiling 3A	2.98	1.23	0.25	0.23	0.17	0.10	0.04	5.00
Conventional tillage+subsoiling 1C	2.61	1.31	0.52	0.34	0.14	0.06	0.03	5.00
Conventional tillage+subsoiling 2C	2.69	1.26	0.52	0.33	0.13	0.05	0.03	5.00
Conventional tillage+subsoiling 3C	2.77	1.21	0.52	0.32	0.12	0.04	0.02	5.00

Fallow land+no-subsoiling 1A	4.62	0.26	0.06	0.02	0.02	0.02	0.00	5.00
Fallow land+no-subsoiling 2A	4.46	0.42	0.05	0.02	0.03	0.02	0.02	5.00
Fallow land+no-subsoiling 3A	4.53	0.35	0.05	0.02	0.03	0.02	0.01	5.00
Fallow land+no-subsoiling 1C	3.96	0.75	0.15	0.07	0.04	0.02	0.01	5.00
Fallow land+no-subsoiling 2C	3.97	0.77	0.14	0.07	0.04	0.01	0.00	5.00
Fallow land+no-subsoiling 3C	3.96	0.73	0.16	0.07	0.05	0.02	0.01	5.00
Fallow land+subsoiling 1A	3.05	1.51	0.19	0.09	0.05	0.07	0.04	5.00
Fallow land+subsoiling 2A	3.24	1.32	0.20	0.11	0.05	0.05	0.03	5.00
Fallow land+subsoiling 3A	3.43	1.13	0.21	0.14	0.05	0.03	0.01	5.00
Fallow land+subsoiling 1C	3.24	0.93	0.34	0.29	0.13	0.05	0.03	5.00
Fallow land+subsoiling 2C	3.14	0.87	0.37	0.34	0.18	0.06	0.04	5.00
Fallow land+subsoiling 3C	3.03	0.79	0.40	0.40	0.24	0.08	0.05	5.00

The Arabic numbers represent the replications while the alphabets A and C represent the horizons 0-30 and 60-90 cm.

1.3 Bulk Density

Soil depth (cm)	Bulk Density		Rep1	Rep 2	Rep 3	Mean
0-30	Fallow	No Subsoiling	0.76	0.73	0.75	0.75
		Subsoiling	0.64	0.62	0.62	0.63
	Conservation	No Subsoiling	0.76	0.78	0.76	0.77
		Subsoiling	0.68	0.72	0.70	0.70
	Conventional	No Subsoiling	0.61	0.58	0.60	0.60
		Subsoiling	0.62	0.58	0.64	0.61
30-60	Fallow	No Subsoiling	0.43	0.50	0.50	0.48
		Subsoiling	0.61	0.58	0.54	0.58
	Conservation	No Subsoiling	0.51	0.52	0.44	0.49
		Subsoiling	0.53	0.50	0.54	0.52
	Conventional	No Subsoiling	0.47	0.46	0.50	0.48
		Subsoiling	0.54	0.59	0.57	0.57
60-90	Fallow	No Subsoiling	0.82	0.79	0.73	0.78
		Subsoiling	0.75	0.80	0.73	0.76
	Conservation	No Subsoiling	0.82	0.83	0.83	0.83
		Subsoiling	0.74	0.69	0.74	0.72
	Conventional	No Subsoiling	0.80	0.78	0.74	0.78
		Subsoiling	0.78	0.79	0.83	0.80

1.4 Infiltration Rate

Soil depth (cm)	Infiltration		Rep1	Rep 2	Rep 3	Mean
0-30	Fallow	No Subsoiling	15.5	12.5	11.0	13.0
		Subsoiling	10.0	12.0	11.0	11.0
	Conservation	No Subsoiling	4.0	3.5	4.5	4.0
		Subsoiling	2.5	3.5	3.0	3.0
	Conventional	No Subsoiling	4.5	2.5	2.0	3.0
		Subsoiling	11.0	11.0	8.0	10.0
30-60	Fallow	No Subsoiling	10.5	10.5	9.0	10.0
		Subsoiling	7.5	9.0	7.5	8.0
	Conservation	No Subsoiling	8.0	11.0	11.0	10.0
		Subsoiling	7.5	7.5	6.0	7.0
	Conventional	No Subsoiling	11.5	10	11.5	11.0
		Subsoiling	7.5	7.0	8.0	7.5
60-90	Fallow	No Subsoiling	4.0	2.0	3.0	3.0
		Subsoiling	2.5	3.0	2.0	2.5
	Conservation	No Subsoiling	1.5	3.0	1.5	2.0
		Subsoiling	4.5	2.5	2.0	3.0
	Conventional	No Subsoiling	3.5	2.0	2.0	2.5
		Subsoiling	2.0	3.0	1.0	2.0

1.5 Hydraulic Conductivity

Soil depth (cm)	Hydraulic conductivity		Rep1		Rep 2		Rep 3	
			-5cm	-15cm	-5cm	-15cm	-5cm	-15 cm
0-30	Fallow	No Subsoiling	15.5	5.5	12.5	7.0	11.0	7.0
		Subsoiling	10.0	4.5	12.0	6.0	11.0	4.5
	Conservation	No Subsoiling	4.0	2.0	3.5	4.0	4.5	3.0
		Subsoiling	2.5	1.5	3.5	2.5	3.0	2.0
	Conventional	No Subsoiling	4.5	0.5	2.5	3.0	2.0	2.5
		Subsoiling	11.0	7.5	11.0	6.0	8.0	6.0
30-60	Fallow	No Subsoiling	10.5	2.0	10.5	5.0	9.0	3.5
		Subsoiling	7.5	2.0	9.0	4.0	7.5	4.5
	Conservation	No Subsoiling	8.0	2.0	11.0	3.5	11.0	3.5
		Subsoiling	7.5	2.5	7.5	4.0	6.0	2.5
	Conventional	No Subsoiling	11.5	4.0	10.0	3.0	11.5	5.0

		Subsoiling	7.5	3.0	7.0	3.0	8.0	4.5
60-90	Fallow	No Subsoiling	4.0	3.5	2.0	2.0	3.0	2.0
		Subsoiling	2.5	0.0	3.0	3.0	2.0	3.0
	Conservation	No Subsoiling	1.5	3.0	3.0	1.0	1.5	0.5
		Subsoiling	4.5	1.5	2.5	3.0	2.0	3.0
	Conventional	No Subsoiling	3.5	0.5	2.0	2.5	2.0	3.0
		Subsoiling	2.0	1.0	3.0	1.5	1.0	2.0