ASSESSMENT OF SOIL COMPACTION LEVELS BY FARM MACHINERY IN CULTIVATED SANDY LOAM SOILS

BY

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DECLARATION

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DEDICATION

I am dedicating this work to my family especially my wife Edna, children Kevin and Villarine for their support and encouragement.

ABSTRACT

The increasing soil degradation due to soil compaction may be linked to the increase in weight of agricultural machinery, in the more use of machinery even under unfavorable soil conditions and to poor crop rotation. The objective of the research was to assess the levels of soil compaction in cultivated fields. The research experiment was done in Elfam farm in Moiben Sub County, Uasin Gishu County, Kenya. The soils type was classified as Ferralsols with sandy loam texture. A four wheeled 70 kN tractor was used in the experiments. A multiple linear regression was used to describe the relationships of load, depth and number of passes for both bulk density and penetration resistance. The experiment was conducted at three levels of normal loads of 26 kN, 30 kN and 34 kN at four levels of number of passes 1,5,10 and 15 all with three replications. The field bulk density and penetration resistance were determined at varying levels of loading and number of passes using sand replacement method and Dynamic cone penetrometer respectively. The data was analyzed using statistical software for analysis of variance (ANOVA) at 95% confidence level and $p < 0.05$. From the results the highest bulk density at 34 kN and 15 passes was 1513 kg/m^3 on the top soil. The lowest bulk density was 1116 kg/m^3 on the subsoil layer below 45cm at 26 kN and one pass. The highest penetration resistance was found to be 52.50 J/cm at 30 kN and a depth below 45cm. The lowest penetration resistance obtained was 9.52 J/cm at 26 kN on the top soil layer. During the test period the moisture content average was 25%. The findings indicated that there was an increase in bulk density with the increase of loading and number of passes. The penetration resistance increased with loading, number of passes and depth. The increased loading and number of passes was particularly found to affect the soil layer above 45cm. From the study it was found that the effect of number of passes on bulk density increased with the increase in the number of passes. Also, loading and number of passes were found to have significant impact on penetration resistance. The coefficients of determination (R^2) for bulk density and penetration resistance were found to be of 0.8822 and 0.8674, respectively. The relative compaction from the test results indicate that the soil was 95.5% compacted.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BD	Bulk density
BS	British standards
DCP	Dynamic cone penetrometer
FEM	Finite Element Method
MDD	Maximum dry density
OMC	Optimum Moisture Content
ρ	Bulk density
PCA	Principal Component analysis
PR	Penetration resistance
USDA	United States Department of Agriculture

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I would only end by saying thank you.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Increased demand for food due to increasing population coupled with limited land has put a lot of pressure on land to increase output per unit area through mechanization. Soil compaction is an environmental problem (Keller et al., 2012). It is one of the causes of increased soil erosion and flooding (McKenzie, 2010). In addition, it also affects availability of nutrients and pesticide leaching to the groundwater (Lipiec *et al*., 2012).

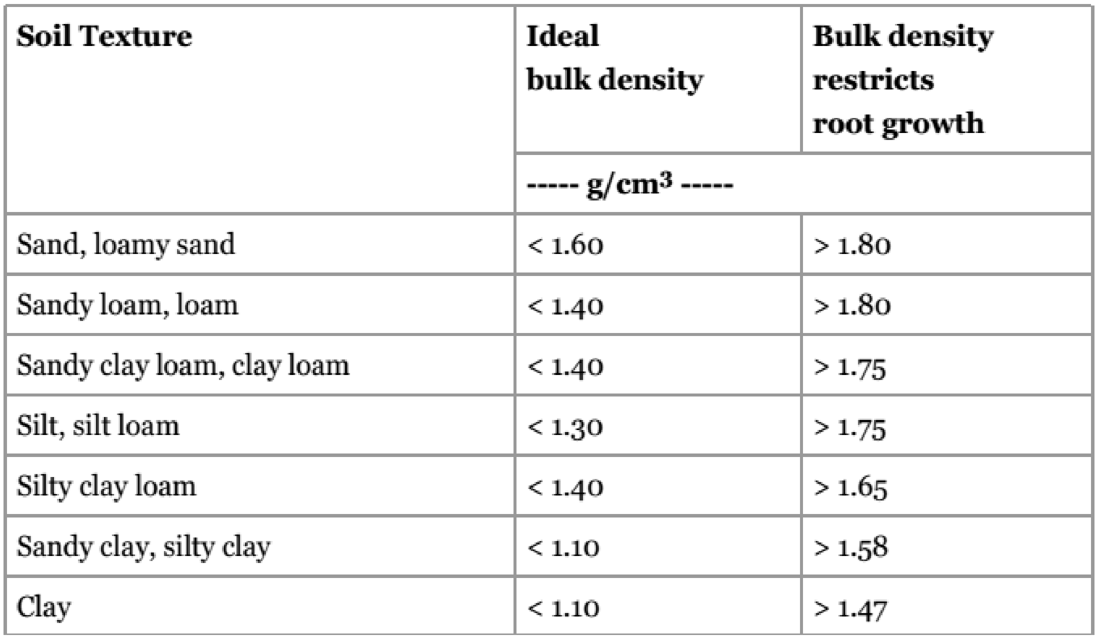
1.1.1 Effect of soil type on soil compaction

The most direct effect of soil compaction is an increase in the bulk density of soil. Optimum bulk densities for soils depend on the soil texture (Table 1). Whenever the bulk density exceeds a certain level, root growth is restricted. No-till soils often have a higher bulk density than recently tilled soils. However, because of higher organic matter content in the topsoil and greater biological activity, the structure of a no-till soil may be more favorable for root growth than that of a cultivated soil, despite the higher bulk density.

1.1.2 Penetration resistance and root penetration

Root penetration is limited if roots encounter much resistance. Research on completely disturbed soil packed to different densities has shown that root growth decreases linearly with penetration resistance starting at 689.5 kpa until root growth completely stops at 2068.4 Kpa. Penetration resistance is a better indicator of the effects of soil compaction on root growth than bulk density because results can be interpreted independent of soil texture (Taylor *et al.*, 1966).

Table 1: Ideal and root-restricting bulk densities.



Soil Texture	**Ideal bulk density**	**Bulk density restricts root growth**
	----- g/cm³ -----	
Sand, loamy sand	< 1.60	> 1.80
Sandy loam, loam	< 1.40	> 1.80
Sandy clay loam, clay loam	< 1.40	> 1.75
Silt, silt loam	< 1.30	> 1.75
Silty clay loam	< 1.40	> 1.65
Sandy clay, silty clay	< 1.10	> 1.58
Clay	< 1.10	> 1.47

(Sourse Soane et al., 1998)

Soil compaction is recognized as one of the major threat to soil quality. There have been efforts to ameliorate compacted subsoil by mechanical deep-loosening but it is very expensive and often fails. The increasing soil degradation due to soil compaction may be linked to the increase in weight of agricultural machinery (Schjønning *et al*., 2009), in the more intense use of machinery even under unfavorable soil conditions and in addition to poor crop rotation. From an agronomic point of view, soil compaction leads to increased root growth and plant development resulting to a reduction in crop yield (Håkansson & Reeder, 1994). Soil compaction also depends on the type of soil, texture, topography and moisture (Alukukku et *al.*, 2012). Subsoil compaction may persist for a very long time and is hence a threat to the long-term productivity of the soil (Etana & Håkansson, 1994).The increased energy requirement also negatively influences the farmer's budget: the costs for fuel are high compared with the income from yield, and therefore, it is very important to note that the costs for tillage must be minimized in order to optimize the profit. The amount of energy consumption in tillage (especially in primary tillage) is quite high compared with other farming operations. It is contributing to the persistence of food insecurity due to reduced yields per unit area. Most large scale farmers use heavy machinery and equipment. The manner in which machinery are operated in the fields is haphazard and the operations go beyond the onset of the rainy season. Mechanization of field operations is developed with a full focus on economic profitability. As the hired contractors carry out the various farm operations there is no attention of preventing damage to the soil quality as the contractors are focused on output e.g. in terms of hectares ploughed rather than the soil's quality as a growing medium for crop (Alukukku *et al.*, 2012).

It is also believed that the risk of undesirable changes in soil structure can be minimized by limiting the mechanically-applied stress to below a threshold stress (Dawidowski *et al.*, 2001), termed the pre-compression stress. While the concept of pre-compression stress as a threshold between reversible and irreversible strain (Horn *et al.*, 1994) is widely used, it has been scarcely tested in combination with wheeling experiments in the field. The impact of agricultural machinery on soil properties may be simulated by means of soil compaction models, which are an important tool for developing strategies for prevention of soil compaction.

Soil compaction of the agricultural soil is a global concern to engineers, soil scientists and farmers due to use of large and heavy farm vehicles. It is for this reason that Elfam farm was chosen for experimentation because it is fully mechanized with heavy machinery. It is a real threat to intensification of crop production due to adverse effects associated with it. There is a decrease in crop yield and increase in management costs in areas where soil compaction is prevalent. It also has a negative effect on the environment for example soil erosion, leaching of nutrients, pollution of water bodies and greenhouse gases production.

It has been accelerated by the use of large and heavy machinery and equipment under unfavorable soil conditions. The farming community is solely driven by profitability and without any thought of preserving the soil for tomorrow. Farming community also believed that sub-soiling once in a while will be able to address the issue once their unit production has gone down eroding their profit margins. There is also another school of thought that as long as you are not using a disc or a mouldboard plough no soil compaction will occur, as such they have resorted to using spring-tined chisel plough mostly which require a lot of power (Bottinelli *et al.*, 2014). Soil compaction which is a physical form of soil degradation is a subject that is attracting increasing concern worldwide. Not much has been done in Kenya to study, document and make recommendations on the impact of soil compaction due to the use of heavy farm machinery despite being one of the threats soil degradation. This research study was then undertaken to ascertain the extent of soil compactions in cultivated sandy loam soils.

1.2 Statement of the Problem

Soil compaction being the main physical component of soil degradation is currently a major global problem because of its short and long term effects on the soil properties considered to be the main resource in crop production. Due to compaction, the soil not only becomes denser, but also stronger. Consequently, the soil is more difficult to till and its friability (ability to fragment) is decreased (Keller T, 2004). As a result of the stronger soil, higher draught is required which means increase in fuel consumption for tillage. Compacted soil will not allow roots to fully develop and restrict their growth downwards leaving only horizontal growth with the net effect of limiting their water uptake, nutrients extraction and poor anchoring of the crop (McKenzie, 2010). Other consequents of compacted soil are poor percolation of water, increased surface run off, increased soil erosion and direct washing of herbicides to streams and rivers. This has impacted negatively on the soil physical properties and the yield as the soil conditions are not favorable for crop production. Also unnecessary deep ripping of the soil will expose the soil to further degradation by weakening the soil structure. This research study was then undertaken to ascertain the extent of soil compactions in sandy loam soils.

1.3 Study justification

The study has the following justifications;

i) The results will be used to create awareness on the major effects of compacted soil to the farming community and on what measures they should undertake to prevent or mitigate soil compaction in their quest of improving production and profitability.

ii) It forms a database on the effects of heavy farm machinery and equipment on soil properties and the effect on the yields per unit area.

1.4 Main Objective

The broad objective of the study was to assess the levels of soil compaction by farm machinery in cultivated sandy loam soils.

1.4.1 The Specific Objectives were:-

i) To determine the effect of loading and number of passes on bulk density by farm machinery.

ii) To determine the effect of loading and number of passes on penetration resistance by farm machinery.

iii) To determine the coefficients for penetration resistance and bulk density with respect to load, depth and number of passes using multiple linear regressions.

1.5 Hypotheses

That there is no effect of increasing axle load and number of passes on bulk density and penetration resistance at selected depths of the soil.

1.6 Scope and limitation

This research was limited to testing of bulk density and soil penetration resistance within the study area. The number of passes was limited to 1,5,10 and 15 passes with the total loads ranging from 7 – 10 metric tons. The research findings are applicable only to the sandy loam soils. There are other factors which have an influence on soil compaction such as moisture content and soil texture but they were not considered as variables during this study. The soil is homogeneous and isotropic within the study area. During land preparation the soil was dry and hence no compaction occurred during this operation but during the subsequent operations. The study considered the effects of axle loads and the number of passes as the main factors affecting soil compaction as a result of using heavy farm machinery and equipment.

1.7 Layout of the thesis

This thesis is made up of five chapters covering the various parts. Chapter one is the introduction of soil compaction, background information, the statement of the problem, the broad and specific objectives, study justification, hypotheses, and limitation. Chapter two comprises of literature review of the various factors contributing to soil compaction. The methodology, materials, the details of data collection methods and data analysis methods are all captured in chapter three. The study area is well covered in this chapter. Results and discussion are in chapter four where the results and discussion are articulated. Finally chapter five covers conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil compaction

Soil compaction causes changes in pore space, size, distribution, and soil strength. One way to quantify the change is by measuring the bulk density. As the pore space is decreased within a soil, the bulk density is increased. Soils with a higher percentage of clay and silt, which naturally have more pore space, have a lower bulk density than sandy soils. An ideal silt loam soil is made up of 45% of mineral particles, organic matter 5%, Air 25% and water 25% (Figure 1) compaction effects on soil macropore geometry and related parameters for an arable field (Hyemin *et al.*, 2010).

On the other hand soil compaction increases soil strength which is the ability of soil to resist being moved by an applied force. In a compacted soil the roots must exert greater force to penetrate this layer of closely packed soil.

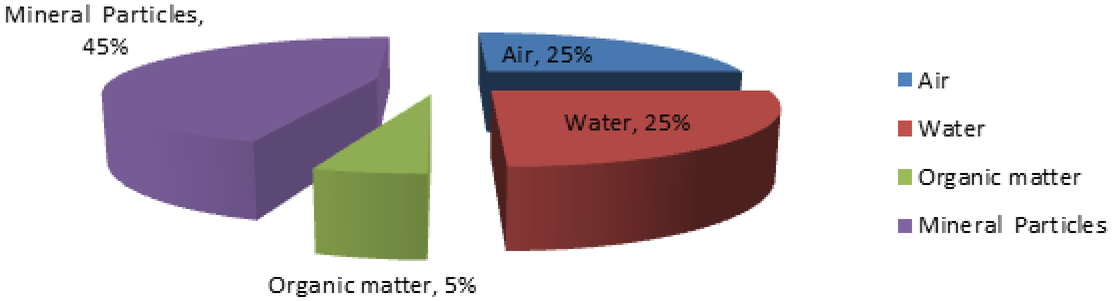


Figure 1: Composition of an ideal silt loam soil

(Source: Hyemin *et al.*, 2010)

Soil is subjected to compaction effects during intensive agriculture through the use of machinery and animals. The compressive effects may adversely affect water and air movement, seedling emergence and root penetration (Marshall *et al.,* 1999). Soil compaction is one of the major problems facing modern agriculture. Overuse of machinery, intensive cropping, and short crop rotations, intensive grazing and inappropriate soil management leads to compaction. Soil compaction occurs in a wide range of soils and climates. It is exacerbated by low soil organic matter content and use of tillage or grazing at high soil moisture content. Soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertilizer requirement and increasing production cost. A detrimental sequence then occurs of reduced plant growth leading to lower inputs of fresh organic matter to the soil, reduced nutrient recycling and mineralization, reduced activities of micro-organisms, and increased wear and tear on cultivation machinery (Hamza *et al.,* 2005).

Though soil compaction is useful in other fields but it has a disastrous effect on agricultural land. Compacted soil will not allow water to infiltrate deep into the soil but instead increases surface runoff causing soil erosion and flooding. It also increases the movement of pesticides and leaching of nutrients indirectly through runoff. Soil compaction adversely affects soil physical properties especially storage, supply of water and nutrients, through increase in soil bulk density, soil strength, decrease in porosity, soil water infiltration, and water holding capacity (Hyemin *et al.,* 2012). These adverse effects reduce fertilizer efficiency and crop yield, increase water-logging, runoff and soil erosion with undesirable environmental pollution problems (Hamza *et al.,* 2005).It has been shown by recent studies that use of large and heavy machinery reduce the pore size distribution of the soil. While studying soil macro porosity characteristics (shape, size and orientation) it was found that they were affected by use of heavy traffic. Heavily compacted soils contain few large pores and have a reduced rate of both water infiltration and drainage from the compacted layer. This occurs because large pores are most effective in moving water through the soil when it is saturated (Lipiec *et al.,* 2012). In addition, the exchange of gases slows down in compacted soils, causing an increase in the likelihood of aeration-related problems *(*Bottinelli *et al.,* 2014).

2.1.1 Bulk density

It is defined as the ratio of the mass of soil to its total volume they occupy (solids and pores) It is affected by the structure of the soil, which is the looseness, degree of compaction, swelling and shrinkage characteristics. It depends on the clay content and the wetness. It can be referred to depending on how the volume is obtained since it changes with compaction, shaking or even tapping. Soil bulk density can be expressed as dry bulk density ρ_b (equation 2.1) or wet bulk density ρ_t (equation 2.2) (Hillel, 1980).

$$\rho_b = \frac{M_t}{V_t} = \frac{M_s}{V_s + V_a + V_w}\ g/cm^3 \qquad \text{Eqn (2.1)}$$

Where $\boldsymbol{\rho_b}$ is the dry bulk density, M_s Mass of solids, M_t total mass of wet solids, V_t is the total volume, V_s volume of solids, V_a volume of air and V_w volume of water

$$\rho_t = \frac{M_t}{V_t} = \frac{M_s + M_w}{V_s + V_a + V_w}\ g/cm^3 \qquad \text{Eqn (2.2)}$$

Where; ρ_t is the wet bulk density and M_w is the mass of water.

2.1.2 Types of Soil compaction.

It is almost impossible to avoid topsoil compaction but tillage and natural processes can re-loosen the topsoil. Sub-soil compaction occurs on the lower layers of the soil. It is mainly caused by excessive loading of the soil from above. Subsoil compaction is much more persistent and difficult to remove (Schjønning *et al.*, 2009).

2.1.3 Causes of soil compaction

The forces which can compact the soil can be either natural or man-induced. These forces can be great, such as from a tractor, combine or tillage implement, or it can be as small as a raindrop. Raindrop impact is a natural cause of soil compaction and usually affects less than 12mm thick of the soil surface. It may prevent seedling emergence. Continuous use of mouldboard plough or disc plough at the same ploughing depth will cause serious tillage hard pans (compacted layers) just below the ploughing depth of the tillage implement in some soils. This tillage hard pan is relatively thin with thickness ranging from 25mm to 50mm. Generally, it may not have any significant effect on the crops. Wheel traffic is without a doubt the major cause of soil compaction. The over-compacted soils are generally found along the wheel tracks and on the turning strips at field head lands (Cyganow and Kloczkow, 2001). The effects are more marked on topsoil (Balbuena *et al.,* 2000). It has been shown that subsoil compaction is related to total axle load and independent of ground pressure (Botta *et al.*, 2009).

With increasing farm size, the time required to carry out all the farm operations is often limited, as a result the size and weight of tractors have increased from less than 3 tons in the 1926's to over 20 tons today for the big four-wheel-drive units. This is of special concern because some farm operations such as planting, spraying and making of silage are often done when the soil is already wet and cannot support the heavy machinery (Figure 2). It is one of the major causes of subsoil compaction (*Wolkowski* and Lowery, 2008). Wheel smearing is another cause of soil compaction which realigns soil particles in a thin layer from random to parallel orientation by slipping wheels (extreme shearing). Another cause is the trend towards a limited crop rotation, which has an effect of limiting the crops with different rooting systems and their beneficial effects on breaking subsoil compaction. Stock trampling is also a significant cause of compaction, especially in the surface horizon of finer textured soils, but the effects are confined to the upper 15 cm of the soil profile.

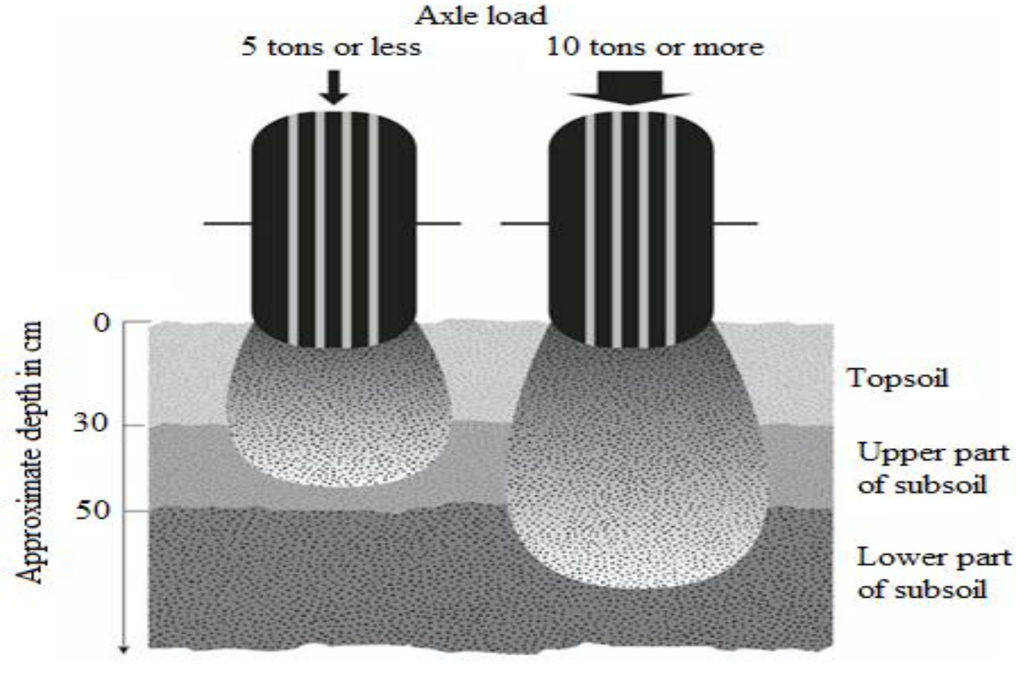


Figure 2: Effect of axle load on soil compaction.

(Van den Akker *et al.*, 1994).

2.1.4 Compression stresses on the topsoil

The stresses exerted on a soil depend on the nature of the object imposing the pressure. Dexter and Tanner (1973) quoted the maximum pressures generated by animals and tractors as shown on Table 2.

Table 2: Maximum pressure generated by different tractors and animals

Source	Stress (MPa)
Horses and cows	0.16 - 0.39
Sheep/humans	0.06 - 0.10
Small tractors < 2 tons	0.03 - 0.10
Large tractors (2-axle)	0.1 - 0.2

2.2 Factors affecting soil compaction

Soil compaction initially increases with increase in soil moisture up to a certain limit where the soil attains its maximum dry density (MDD). This limit is normally referred to optimum moisture content (OMC). Any further increase in moisture will result in the soil exhibiting its plastic properties. The optimum soil moisture varies depending on the composition of the soil (Hamza *et al.,* 2005).

The axle load determines the depth to which the effect on the soil occurs. Heavier traffic or machinery has its effects going deeper into the soil more than lighter traffic on the same soil. When tyre pressure is increased, the surface area of the tyre lugs in contact with the soil decreases. The force will then be carried by a smaller surface area of the soil. The net effect on the soil will be deeper than when the pressure is lower. Low pressure means that the surface area in contact with the tyre lugs also increases and hence less compaction of the soil.

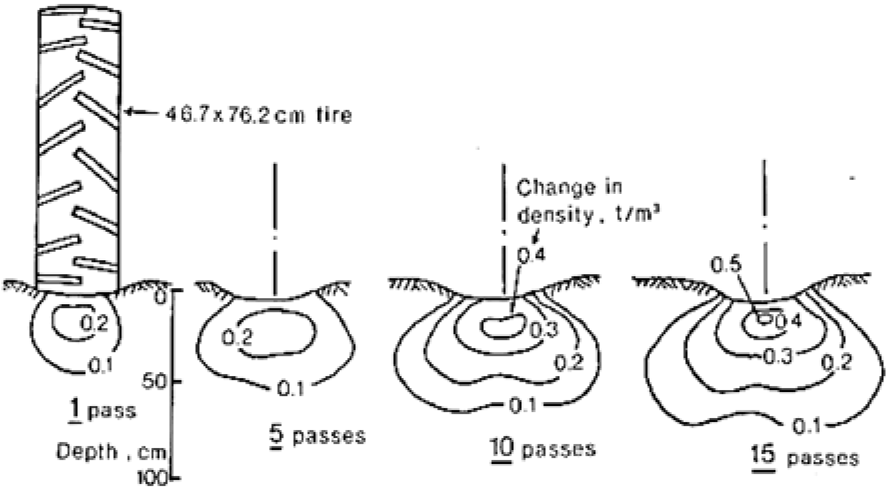


Figure 3: The effect of repeated passes on soil compaction beneath pneumatic tyre. (Source: Wolkowski and Lowery, 2008)

The number of passes the traffic makes through the same point, though normally the first pass causes between 80-90% of compaction as illustrated by figure 3 increases the effect on the soil both at the surface and deeper (Wolkowski and Lowery, 2008). A strong soil will withstand higher loads without being adversely affected but weaker soil will be damaged with little loading (Lapen *et al.*, 2001).

2.3 Traffic over the Field and moisture content

The pressure isobars or isobar contours represents the points with equal stress caused by the tyre of a tractor under different soil conditions. These are normally referred to as pressure bulb lines since they resemble a bulb (fig 4).

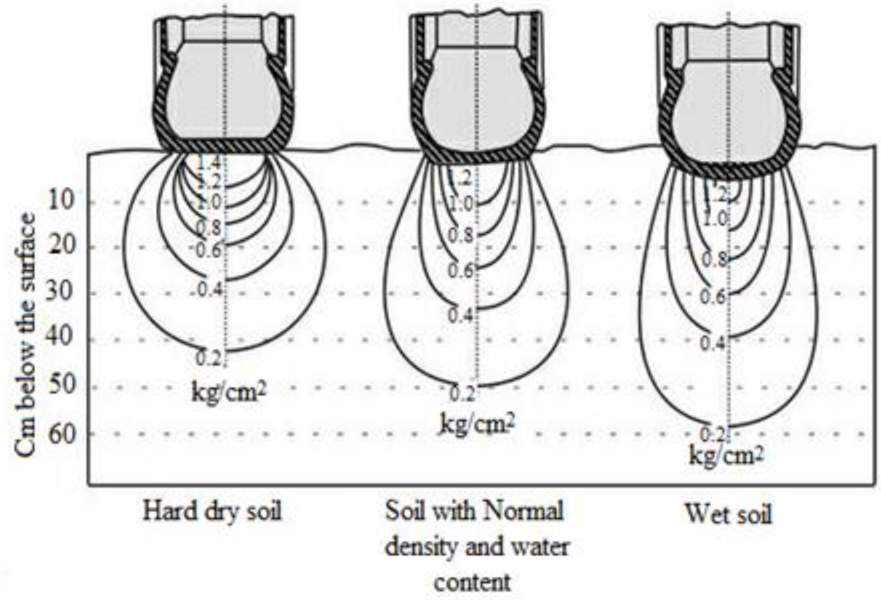


Figure 4: Effect of soil moisture on load penetration under a tractor tire.

(Tyre size 28-71cm; load 748kg; inflation pressure 0.8kg/cm^3)

(Source: adapted from Soehne, 1998).

The isobars are calculated based on the Boussinesq equation (1885) equation 2.3

$$\sigma_z = \frac{3Q}{2\pi z^2}\frac{1}{[1+(r/z)^2]^{\frac{5}{2}}} \qquad \text{Eqn (2.3)}$$

$$\sigma_z = \frac{Q}{2z^2} I_B \qquad \text{Eqn (2.4)}$$

Where: I_B = Boussinesq stress coefficient and is given by equation (2.5) and illustrated in Figure 5.

$$I_B = \frac{3}{\pi}\frac{1}{[1+(r/z)^2]^{\frac{5}{2}}} \qquad \text{Eqn (2.5)}$$

Where Q , the vertical point load kilonewtons, σ_z vertical stress at that point P due to the load Q in kilonewtons, z is vertical depth of point P from the surface in metres, r, the horizontal distance between point P below the surface and the vertical, axis through the point load Q in metres.

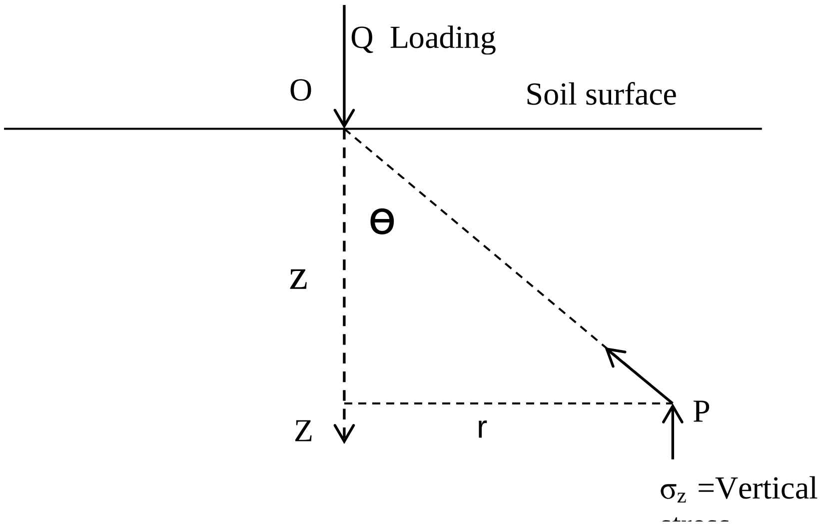


Figure 5: Vertical pressure within a soil mass

(Source: adapted from Keller *et al.,* 2004).

2.4 Mitigation measures

Soil compaction can be reduced or avoided in several ways. Some of the recommended methods for mitigating the effects of soil compaction are; reducing pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil; working soil and allowing grazing at optimal soil moisture; reducing the number of passes by farm machinery and the intensity and frequency of grazing; confining traffic to certain areas of the field (controlled traffic); increasing soil organic matter through retention of crop and pasture residues; removing soil compaction by deep ripping in the presence of an aggregating agent; crop rotations that include plants with deep, strong taproots; maintenance of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil/crop system to resist harmful external stresses (Hamza *et al.,* 2005).

2.5 Conceptual Framework.

Soil compaction is a silent factor which contributes a lot to the systematic destruction of the soil structure and the continuous reduction of yield per unit area. There are quite a number of soil compaction causes namely natural causes like raindrops and trampling by animals, these might prevent seeds from germinating. The major cause is field traffic such as farm tractors, combine harvesters, forage harvesters to mention but a few. Farm trafficking causes both top soil compaction and of serious concern subsoil compaction. Limited soil crop rotation is also another cause of soil compaction. Considering the various soil compaction causes of concern to this study is axle load and number of runs by farm machinery during farm operations from land preparation, harvesting and even post-harvest activities. The test parameters can be many but they all affect the volume of water and air pores in the soil (Figure 6).

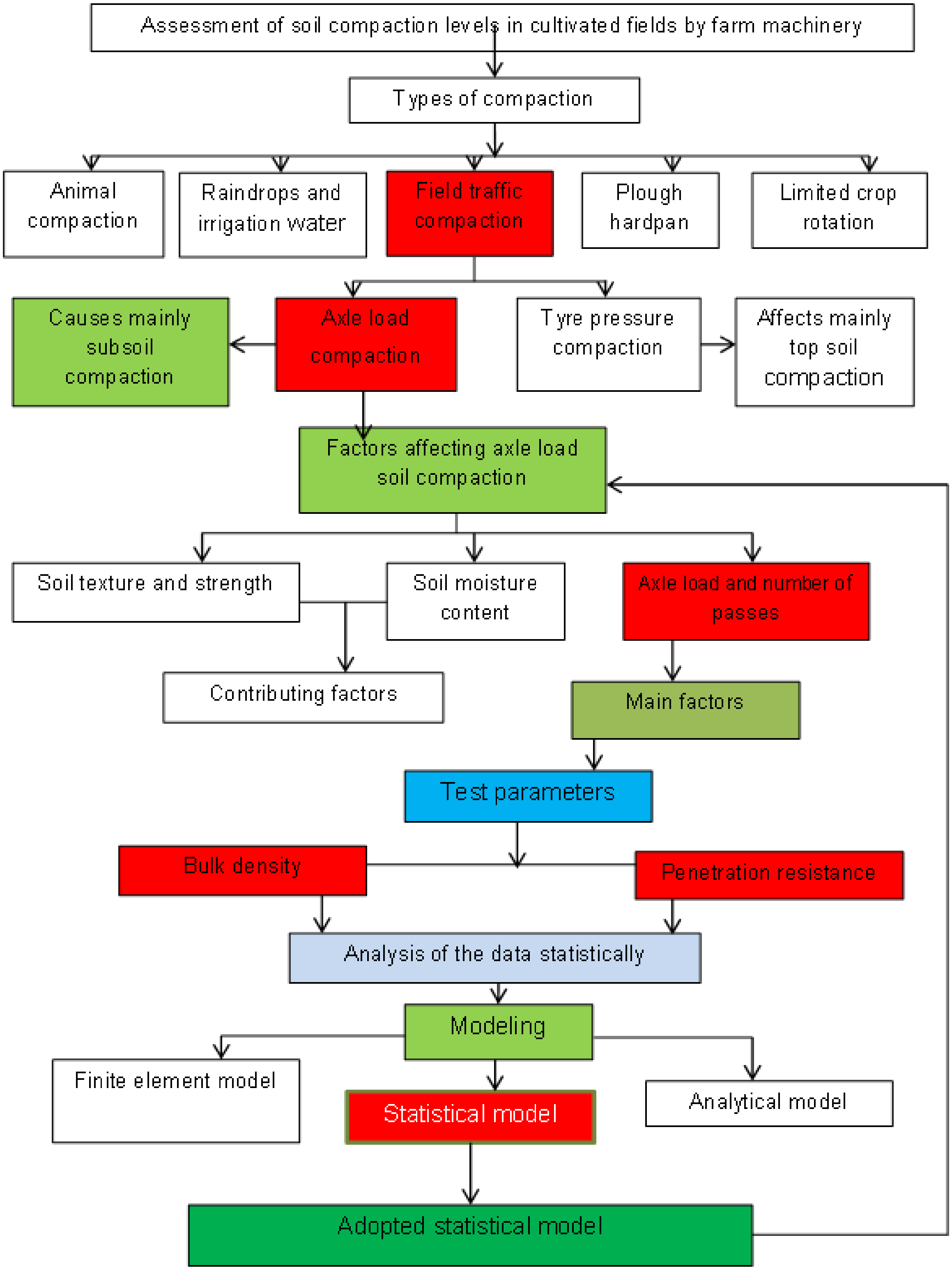


Figure 6: Conceptual framework diagram

(Source: Author, 2015)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

There are several large scale farms in Moiben division with fully mechanized wheat and maize production. Elfam is one of the several large scale farms in the division with 1012 ha of land. Elfam farm is in Moiben sub County of Uasin Gishu County as shown in figure 7. It lies to the North East of Eldoret town. It is about 20 km from the Eldoret town along the Eldoret – Iten road. The farm office has the coordinates 0°35'38.5''N and 35°22'15.7''E and the experimental plot has the coordinates 0°35'26.8''N and 35°22'52.8''E (Figure 8). The altitude is 2200 m above sea level. The prevailing rainfall ranges between 900-1100 mm per annum and the soils type is classified as Ferralsols with sandy loam texture (Jaetzold *et al.*, 2011). The arable land is 607 hectares of which the area under maize is 364 hectares while the remaining is used for wheat growing, barley and *Boma Rhodes* grass for dairy animals (Table 3). The farm operations are fully mechanized from land preparation to harvesting. The crop production is mainly mechanized and machinery sizes vary from 45 hp to 180 hp. The combine harvesters are large with grain tank capacity of up to 6 tons with a choice of wheat or corn harvesting heads. (Elfam reports, 2014)

Land preparation begins between January and February and goes on to the 15th of March. Maize planting period under normal conditions begins from 20th March to 20th April. Wheat from 5th May to 20th June every year. Harvesting of silage crop is normally done when the crop is almost maturing around August and September

Table 3: Crops grown and their hectares for the last 9 years

Crop	Hectares								
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Wheat	607	607	607	587	486	405	283	162	142
Maize	-	-	-	-	20	121	202	324	364
Barley	-	-	-	-	-	-	-	121	101
Boma Rhodes	-	-	-	-	-	-	-	-	24

(Source: Elfam reports, 2014)

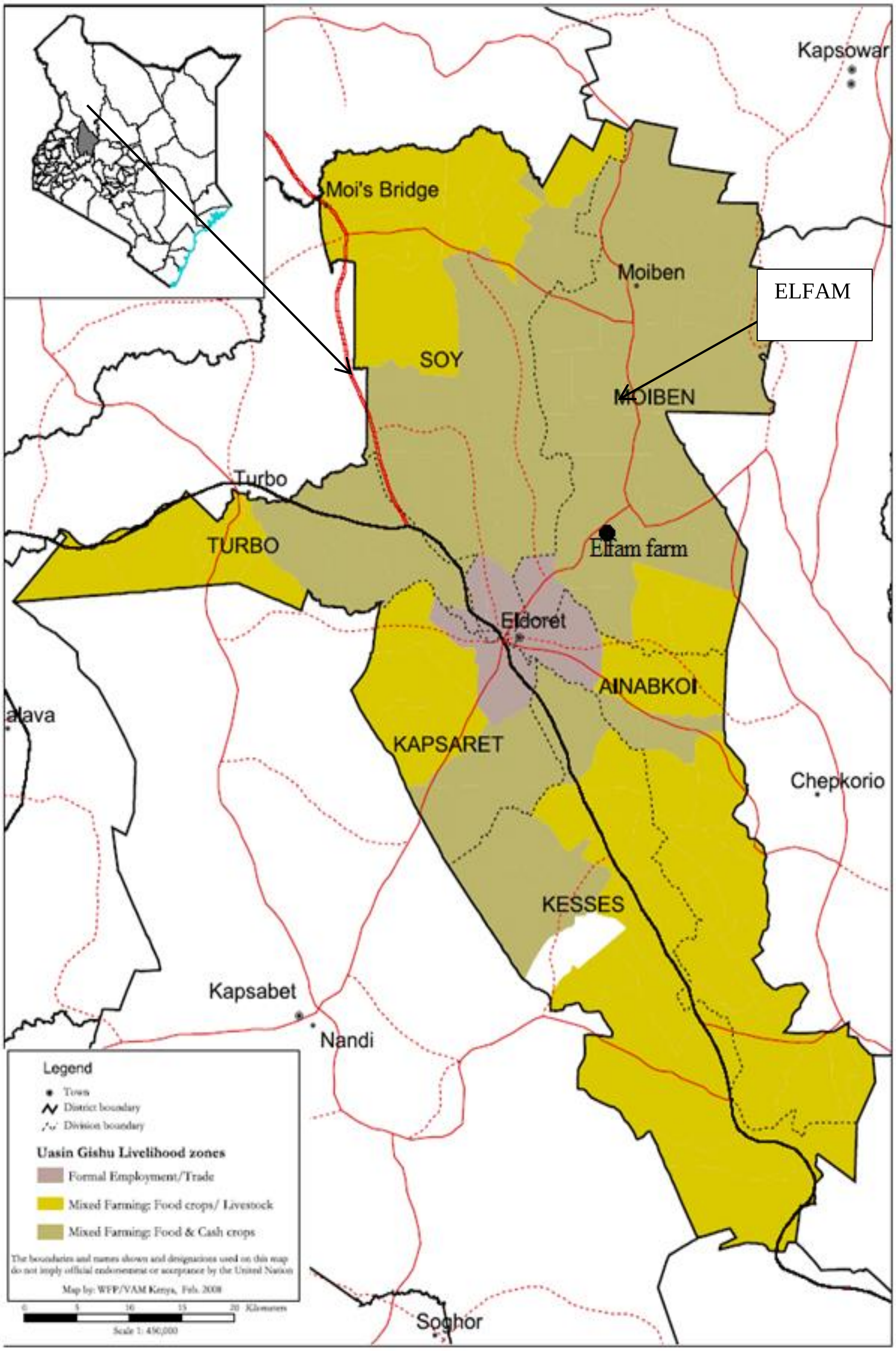


Figure 7: Uasin Gishu county map with livelihood zones shown

(**Source: County Agricultural Office: Eldoret East Sub County, 2012)**

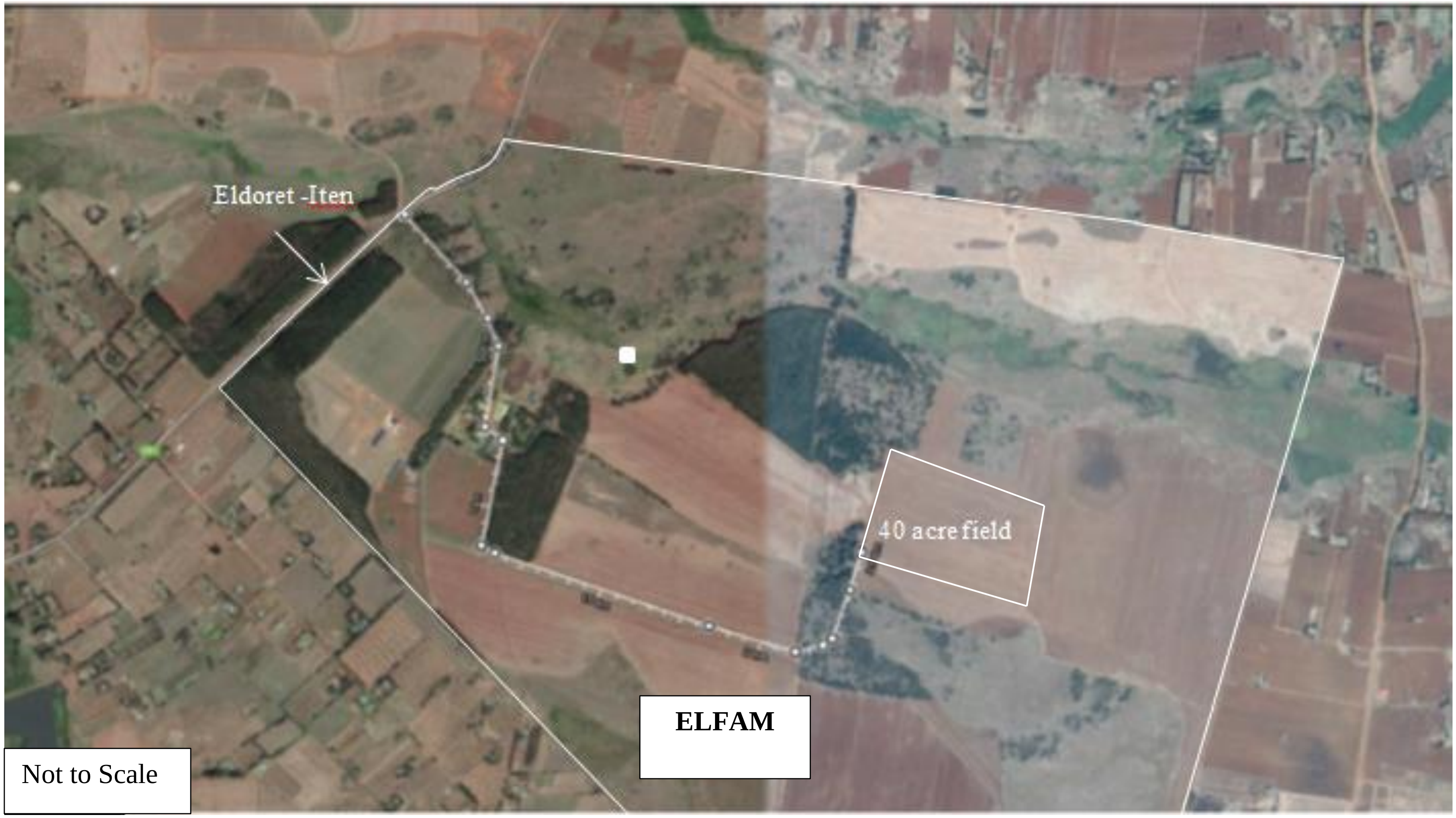


Figure 8: Map showing the “40 acre field” experimental plot.

(Source: Imagery, CNES/Astrium Digital Globe, 2015)

3.1.1 Average wheat and maize yield

The farm has been growing mainly wheat for 20 years but it is only recently that maize production increasing in hectares and at the same time reducing hectares under wheat and the reason because maize production has better yields than wheat (Table 3).The expected maize production yields in the area is up to 7.8 tons/ha

Table 4: **Average yield in tons per hectare for the last 7 years**

Crop	Year						
	2008	2009	2010	2011	2012	2013	2014
Wheat (tons/ha)	3.3	4.0	3.8	0	3.3	0	0
Maize (tons/ha)	0	0	0	5.0	0	5.3	5.6

(Source: Elfam reports, 2014)

3.2 Experimental Design

The experimental design for this field experiment involved two factors; loading *(A)* and number of passes *(B)* with $a=3$ levels of loading and $b= 4$ levels of passes. It is a two factor factorial design with four treatments and one block. Each observation was replicated three times. The experiments were done in a completely randomized two factor factorial design with $a = 4$ level of treatments per factor and $n=3$ replicates. Observations were recorded at depths 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm, loading of 26 kN, 30 kN, 34 kN and number of passes 1, 5, 10, and 15 (Table 4). The numbers of passes were chosen to correspond to the various farm operations (Wolkowski and Lowery, 2008). The normal weight on a single rear tyre 26 kN, 30 kN and 34 kN were arrived at through chassis mechanics calculations (Figure 10) of the normal weight on the rear tyre as per field operations; planting, towing a six ton trailer and a fully loaded combine harvester.

Table 5: Data table for recording the tests for two factor factorial design

Treatments	**No of passes**				**Totals**	**Averages**
	1	5	10	15		
26kN	$y_{111}, y_{112}, y_{113}$	$y_{121}, y_{122}, y_{123}$	$y_{131}, y_{132}, y_{133}$	$y_{141}, y_{142}, y_{143}$	$y_{1\cdot\cdot}$	$\bar{y}_{1\cdot\cdot}$
30kN	$y_{211}, y_{212}, y_{213}$	$y_{221}, y_{222}, y_{223}$	$y_{231}, y_{232}, y_{233}$	$y_{241}, y_{242}, y_{243}$	$y_{2\cdot\cdot}$	$\bar{y}_{2\cdot\cdot}$
34kN	$y_{311}, y_{312}, y_{313}$	$y_{321}, y_{322}, y_{323}$	$y_{331}, y_{332}, y_{333}$	$y_{341}, y_{342}, y_{343}$	$y_{3\cdot\cdot}$	$\bar{y}_{3\cdot\cdot}$
Totals	$y_{\cdot 1\cdot}$	$y_{\cdot 2\cdot}$	$y_{\cdot 3\cdot}$	$y_{\cdot 4\cdot}$	$y_{\cdots}$	
Averages	$\bar{y}_{\cdot 1\cdot}$	$\bar{y}_{\cdot 2\cdot}$	$\bar{y}_{\cdot 3\cdot}$	$\bar{y}_{\cdot 4\cdot}$		$\bar{y}_{\cdots}$

(Source: Montgomery & Runger, 2003)

Where:-

$$y_{i\cdot\cdot} = \sum_{j=1}^{b} \sum_{k=1}^{n} y_{ijk} \qquad \bar{y}_{i\cdot\cdot} = \frac{y_{i\cdot\cdot}}{bn} \qquad i = 1,2,3 \ldots a \qquad \text{Eqn (3.1)}$$

$$y_{\cdot j\cdot} = \sum_{i=1}^{a} \sum_{k=1}^{n} y_{ijk} \qquad \bar{y}_{\cdot j\cdot} = \frac{y_{\cdot j\cdot}}{bn} \qquad j = 1,2,3 \ldots b \qquad \text{Eqn(3.2)}$$

$$y_{ij\cdot} = \sum_{k=1}^{n} y_{ijk} \qquad \bar{y}_{ij\cdot} = \frac{y_{ij\cdot}}{n} \qquad i = 1,2,3 \ldots a\,; \quad j = 1,2,3 \ldots b \qquad \text{Eqn(3.3)}$$

$$y_{\cdots} = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} y_{ijk} \qquad \bar{y}_{\cdots} = \frac{y_{\cdots}}{abn} \qquad \text{Eqn (3.4)}$$

The Equation 3.1, 3.2, 3.3 and 3.4 were used to evaluate the averages on table 4 for the dependent variable y.

3.2.1 Experimental plots layout

The experimental plot was divided into three equal sections L_1, L_2 and L_3 each measuring 400 m x 16 m. Each plot was further divided into four subplots each measuring 100 m x 16 mm (Figure 9). Test pits were marked as indicated in Figure 10. Each plot was treated as indicated on each plot.

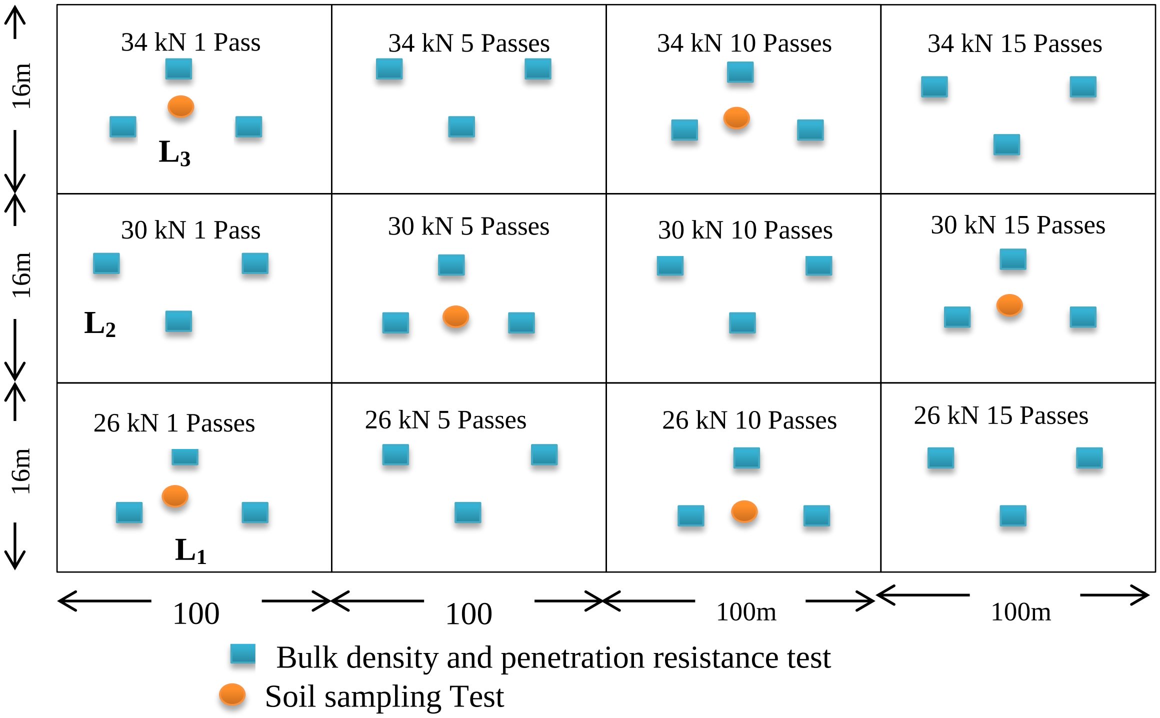


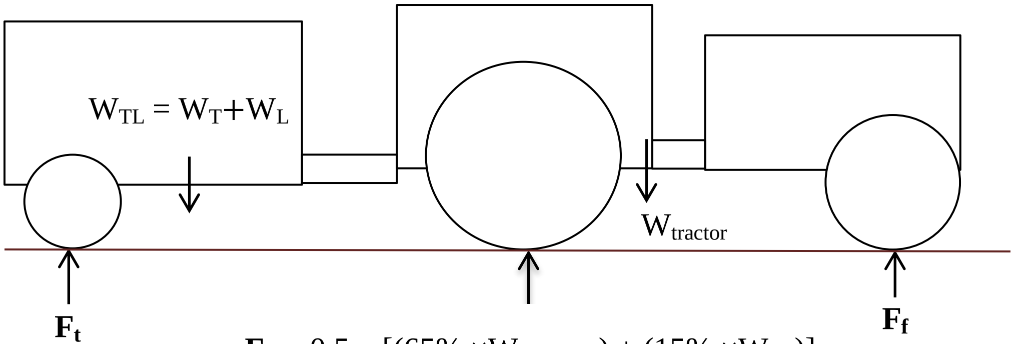
Figure 9: Experimental plots layout

3.3 Machinery and Equipment

During the field tests the machinery, tools and equipment used were a 70 kN four wheel tractors, 60 kN and 120 kN capacity trailer, Dynamic Cone penetrometer (DCP), Sand replacement method equipment, basic soil excavation tools e.g. mattock, spade, chisel, mason hammer and Soil samples collection bags. The weights used in the experimentation were 26 kN, 30 kN and 34 kN. These are the normal weights on a single rear wheel of a tractor representing the various field operations from planting to harvesting. The calculation to obtain these values is shown in Figure 10. The samples collected were taken to the Ministry of Transport and Infrastructure Materials Testing and Research Department laboratory (Eldoret) for the determination of moisture content, standard proctor tests and sieve analysis of the soil.

3.3.1 Tractor data

The weight of the tractor and equipment used was as per manufacturer's specification. The tyre pressure was kept at the recommended inflation of 124.2kPa. The weight on the big rear wheel of the tractor is 65% of the total weight of the tractor ($W_{tractor}$) the weight transfer from the trailer to the tractor rear wheel is 15% of the total weight of the trailer and the load (W_{TL}) (Figure 10 and Figure 11). Therefore the normal force on the rear (F_r) tyres is given by the total. (John Deere operator's manual for 6605, 2001)



$$\mathbf{Fr} = 0.5 \text{ x } [(65\% \times W_{tractor}) + (15\% \times W_{TL})]$$

Figure 10: Free body diagram of a tractor and a trailer

Figure 11: Tractor and loaded trailer used in the experiment
(Source: Author, 2015)

3.4 Experimental Procedure

The experimental plot was chosen such that it was fairly flat and measured 400 m long by 48 m wide. It was then divided into three strips of 400 m long by 16 m wide (Figure 9).

Step 1: The plot was harrowed using a heavy spring tinned harrow then followed by a heavy disc harrow. Final harrowing and raking was done in readiness for planting.

Step 2: Each strip was divided into four sections of 100 m long and 16 m wide

Step 3: Plot L_1 was subjected to a loading of 26 kN by running the tractor at a speed of 7.5 km / hr once

Step 4: The data was randomly taken at the centre of the tyre mark (Figure 13). A set of three replicates were taken at depths of 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm.

Step 5: Step 3 was repeated by operating the tractor through the same tyre mark with the same load of 26 kN four times to make the number of passes to five. Step 4 was then repeated. The same procedure was repeated for 10 and 15 passes on the same plot with the same load (Figure 9).

Step 6: On the second plot L_2 steps 3, 4, and 5 were repeated but with 30 kN load.

Step 7: On the third plot L_3 steps 3, 4, and 5 were repeated but with 34 kN load

3.5 Soil sampling

Random soil sampling was done for use in the standard Proctor test (ASTM D698/ AASHTO T99) at materials laboratory in Eldoret using the standard sampling procedure (ASTM D4700) from experimental plots (Figure 9 & 12) at the following depths 0-30 cm and 30-60 cm.

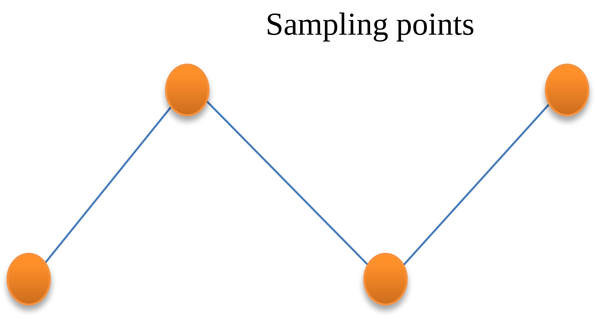


Figure 12: Sampling points design

Figure 13: **Tractor with a fully loaded maize planter making the runs**

(Source: Author, 2015)

3.6 Determination of the effects of load and passes on Bulk density.

The field bulk density *(in situ)* was determined using sand cone replacement method (ASTM 1556) at the following depths 0-15 cm, 15-30 cm 30-45 cm and 45- 60 cm at random. (Cheng *et al.*, 2009)

a) Determination of dry bulk density of sand to be used.

The sand mass in grams (g) was obtained by weighing and using the known volume of the calibrating container in cm^3. The bulk density of sand was calculated as follows:-

$$\rho_1 = \frac{M_1}{V_1} \ g/cm^3 \qquad \text{Eqn (3.5)}$$

Where ρ_1 is the dry density of sand in g/cm^3, M_1 is the mass of sand (g) and V_1 is the volume of sand in cm^3

The above calibration process was used to calibrate dry and clean sand to be used in the field. For every test two sets of calibrated sand was packed in a 3000 g marked container and 6000 g container. Each container had a unique identification label on it.

b) Volume of the test hole (*V*)

In the field the identified test point was leveled until the base plate fitted flat on top (Figure 14). The base plate was then secured using hooks hammered to the ground. The cylinder was then placed on the base plate. The sand in the 3000 g marked container was used to determine the mass of sand in the funnel and base (M_7). After removing the cylinder, the test hole was excavated up to a depth of 15 cm (Figure 14). The soil from the test holes was scooped, packed into a polythene bag, sealed and labeled. The sand in the 6000 g marked container was then poured into the cylinder was used to fill the test hole (M_6). The remaining sand in the cylinder was carefully returned to their specific container. The container was then weighed with the remaining sand. M_6 and M_7 were obtained by subtracting the remaining weights from their respective initial weights of the calibrated clean sand.

The volume of the test hole where soil had been scooped was then determined using the equation 3.6.

$$V = \frac{M_6 - M_7}{\rho_1} \ cm^3 \qquad \text{Eqn (3.6)}$$

Where ρ_1 is the dry density of sand in g/cm3, M_6 is the mass of sand (g) used to fill the test hole and M_7 is the mass of sand in the funnel and base (g)

Figure 14: Preparation of the test hole (Source : Author, 2015)

c) Moisture content determination of the scoped material (ASTM 2216).

The scooped material from the test hole was packed in a sealed polythene sampling bag and taken to the lab for oven drying. The moist mass M_4 was determined. After which two samples were scooped into moisture drying cans per sample. The moisture cans with moist soil sample were each weighed M_2 in grams. After oven drying for 48 hours, weight M_3 in grams was taken. The percentage moisture content w was calculated using equation 3.7. The average percentage moisture content of the two samples was taken.

$$w = \frac{M_2 - M_3}{M_3} \times 100\ \% \qquad \text{Eqn (3.7)}$$

Where w is the moisture content of the material from the test hole in percentage, M_2 is the mass of the moisture sample and the can in (g) and M_3 is the dry mass of moisture sample in (g)

d) Calculation of the dry mass of the material from test hole using equation 3.8

$$M_5 = \frac{M_4}{(0.01)(w + 100)}\ g \qquad \text{Eqn (3.8)}$$

Where w is the moisture content of the material from the test hole in percentage, M_4 is the moist mass of the materials from the test hole in g and M_5 is the dry mass of the materials from the test hole in g

e) Calculation of the bulk density of the materials from the test using equation 3.9.

$$\rho_2 = \frac{M_5}{V}\ g/cm^3 \qquad \text{Eqn (3.9)}$$

Where ρ_2 is the bulk density of the material from the test hole in g/cm^3, M_5 is the dry mass of the materials from the test hole in g and V volume of the test hole in cm^3

$$\rho_2 = 100 \times \frac{M_4}{M_8} \times \frac{\rho_1}{(w + 100)} \; kg/m^3 \qquad \text{Eqn}(3.10)$$

Where $M_8 = M_6 - M_7$ which is the mass of sand in the test hole

3.7 Determination of the effects of load and passes on Penetration resistance

Dynamic cone penetrometer tests (ASTM D3441) were carried out in all the plots, for every loading, number of passes and for all the selected depths. The reading on the scale rule attached to the Dynamic Cone penetrometer (DCP) was recorded for every drop of the hammer or blow by the hammer (Figure 15 and 16).

The different parts of the DCP are summarized by figure 15. It consists of a weight weighing 8 kg, a round smooth steel rod to guide the hammer and attached to the anvil. The 60° replaceable cone tip attached to a 16 mm smooth round steel rod 1m long. A steel rule attached to the anvil and a guide attached to the round steel rod for measuring the depth of penetration in mm. The effective drop height of the weight is 575 mm

3.7.1 Dynamic cone penetrometer

The DCP was placed at the centre of the tyre mark and held vertically. The initial reading on the steel scale rule was recorded once the hammer rested on the anvil. The weight was raised vertically through the effective height of 575 mm and released to freely fall (Figure 16). The reading on the scale rule was recorded for every blow of the hammer until the cone was at least 65 cm to 70 cm below the ground level. The process was replicated three times randomly for every number of passes and loading.

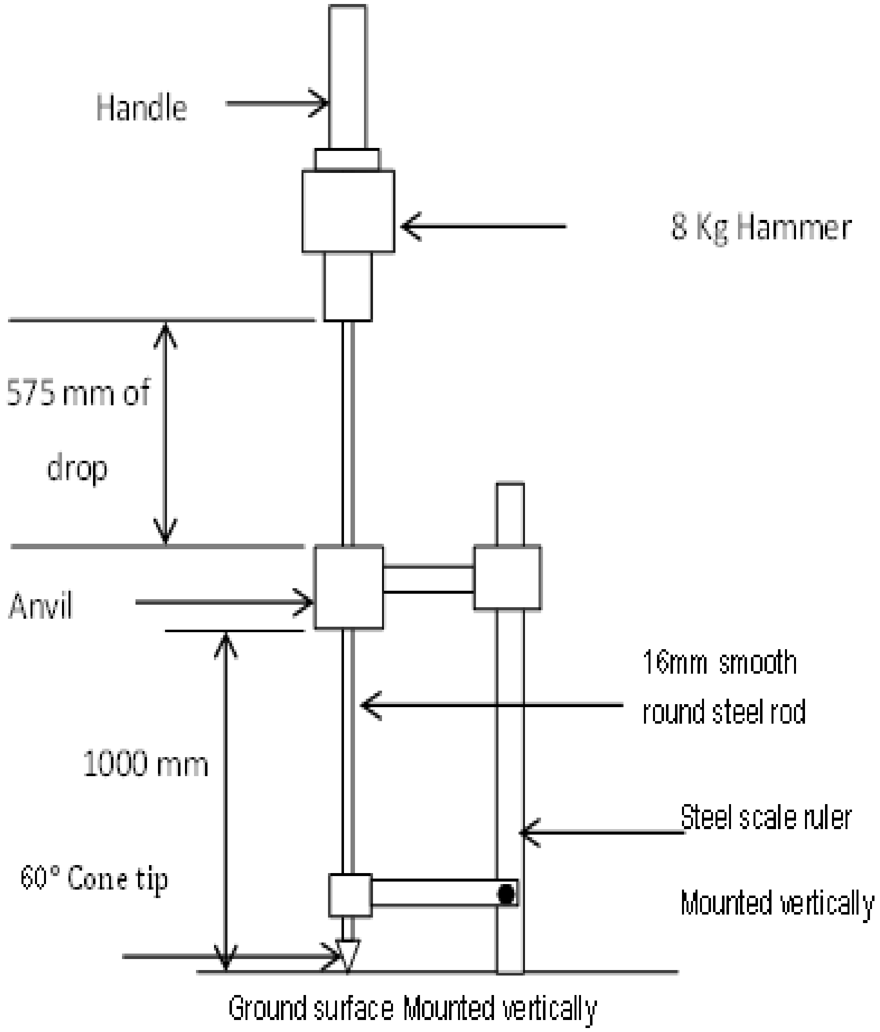


Figure 15: Dynamic cone penetrometer diagram

(Source: Author, 2015)

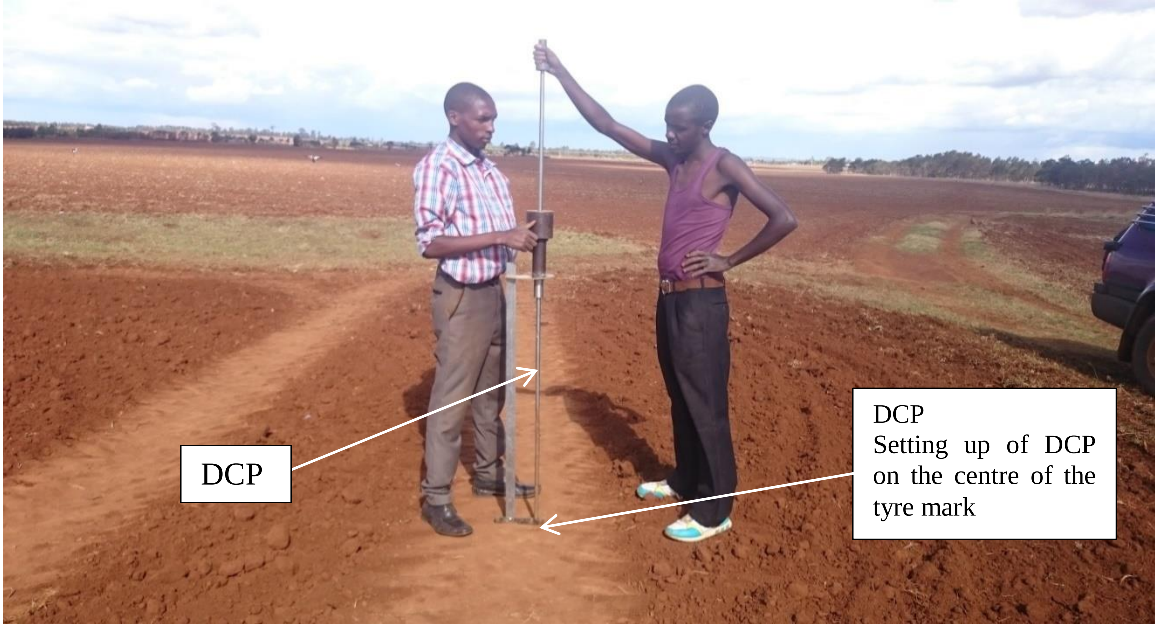


Figure 16: **DCP measurement on the centre of the tyre mark**

(Source : Author, 2015)

For every fall of the 8 kg hammer the energy released to move the cone into the soil is given by:-

$$\text{Kinetic Energy} = \text{Potential Energy} \qquad \text{Eqn (3.11)}$$

$$\frac{1}{2}\text{mv}^2 = \text{mgh} \qquad \text{Eqn (3.12)}$$

$$\text{v} = \sqrt{2\text{gh}} = \sqrt{2 \times 10 \times 0.575} = 3.39\ \text{m/s}$$

$$\text{Kinetic energy} = \frac{1}{2}\text{mv}^2 = \frac{1}{2} \times 8 \times 3.391^2 = 46\ \text{Joules (J)}$$

The Penetration resistance is therefore calculated using the following equation

$$\text{Penetration resistance(PR)} = \left\{\frac{\text{number of blows of the hammer(N)} \times 46}{\text{Depth moved(d) in cm}}\right\}\ \text{J/cm}$$

$$\text{Penetration resistance(PR)} = \frac{\text{N} \times 46}{\text{d in cm}} \ \text{J/cm} \qquad \text{Eqn (3.13)}$$

The penetration resistance results were calculated using equation (3.13).

3.8 Data analysis

The data collected from field experiments were analyzed using a two-way analysis of variance (ANOVA).This analysis was used to test the hypotheses of no main effect of loading (factor A), number of passes (factor B), loading and number of passes interaction effect (AB interaction).The results were evaluated and displayed in ANOVA table for a two factor factorial (Table 6)

Table 6: ANOVA table for a two factor factorial

Source of variations	**Degrees of Freedom**	Sum of squares	**Mean Square**	$\mathbf{F_0}$
A treatments	*a-1*	SSA	$MS_A = \frac{SS_A}{a-1}$	$\frac{MS_A}{MS_E}$
B treatments	*b-1*	SSB	$MS_B = \frac{SS_B}{b-1}$	$\frac{MS_B}{MS_E}$
AB interaction	*(a-1)(b-1)*	SSAB	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1)}$	$\frac{MS_{AB}}{MS_E}$
Error	*Ab(n-1)*	SSE	$MS_E = \frac{SS_E}{ab(n-1)}$	
Total	*Abn-1*	SST		

(Source: Montgomery and Runger, 2003)

F- Distribution was used to test significance in the null hypotheses. Other tests like the 95% confidence interval. The above process was analyzed using Minitab software (v.17) for analysis of variance (ANOVA). The results are displayed in ANOVA table (Table 6) and graphically.

3.9 Determination of regression coefficients for BD and PR

This was determined using multiple linear regression model since the experiment has more than one variables that is loading (L), depth (D) and number of passes (P) based on the multiple linear regression model equation (Montgomery & Runger, 2003)

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \tag{3.14}$$

Where Y is the bulk density in g/cm^3, X_1 is depth in metres, X_2 number of passes, X_3 is the loading in kN, ε is the expected error and β_o is the intercept, β_1, β_2 and β_3 are partial regression coefficients.

If the expected error $E(\varepsilon)$ is assumed to be zero then equation 3.14 becomes

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3.15}$$

The above coefficients measures the expected change in E(Y) when the other two variables are kept constant for example β_1 measures the expected change in Y when β_2 and β_3 are kept constant(Montgomery & Runger, 2003). The regression coefficients were estimated with the use of Minitab statistical software and Microsoft excel. The values of coefficients were replaced in equation (3.15).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General

4.1.1 Sieve analysis

The results of soil sieve analysis using the British Standard (B.S) sieves and samples passing through 5 mm sieve yielded 7.4 % of clay, 32.7 % of silt and 59.6 % of Sand (Table 7). The soil texture based on USDA textural soil triangle (Figure 30) was found to be sandy loam. Generally sandy loam soils have bulk density between 1400kg/m^3 and 1600kg/m^3 (McKenzie, 2010).

Table 7: Soil grading through sieve analysis

Soil	Test point (TP)					
	TP1	TP2	TP3	TP4	TP5	TP6
Clay %	8.2	17.1	6.3	5.2	5.1	2.6
Silt %	30.9	34.1	36.3	33.5	35.7	25.5
Sand %	60.5	48.2	57.5	61.4	58.7	71.4
Texture	Sandy loam	Loam	Sandy loam	Sandy loam	Sandy loam	Loamy sand

4.1.2 Standard Proctor Test

The average maximum dry density (MDD) of the soil was found to be 1376 kg/m^3 and at an average optimum moisture content (OMC) of 29 % (Table 8).

Table 8: Maximum dry density (MDD) and optimum moisture content (OMC) relationship

Test No.	Test Pits (TP)					
	TP1		TP2		TP3	
No	omc %	mdd kg/m^3	omc %	mdd kg/m^3	omc %	mdd kg/m^3
1	24.6	1368	26.6	1340	28.7	1244
2	26.6	1503	28.6	1425	30.7	1334
3	28.6	1475	30.6	1396	32.7	1303
Average	27	1449	29	1387	31	1294
MDD kg/m^3	1376					
OMC %	29					

4.2 Effects of number of passes and loading on bulk density

4.2.1 Effect of the number of passes on bulk density for selected loads on a 0-15 cm soil layer

The results of the varying number of passes for the selected loading of 26 kN, 30kN and 34 kN were plotted against their respective bulk density for every soil layer. In figure 17 the plotted results indicates that loading has an effect on the bulk density as well as the number of passes. The increase in bulk density between a single pass and 5 passes is 5.5% (Table 9) for the lowest loading of 26 kN. The highest increase in bulk density is between the first and 5 passes for all the three levels of loading of 26 kN, 30 kN and 34 kN. The results show that there is an increase in bulk density with the increase in the number of passes (Table 9, 10 & 11). The change in bulk density between the first pass and 5 passes with the change in loading levels of 26, 30 and 34 kN is 5.5, 6.6 and 5.3 %

respectively. The impact of number passes is felt between the first pass and five passes in all the treatments. This clearly confirms that bulk density is affected by change in loading as well as the change in the number of passes.

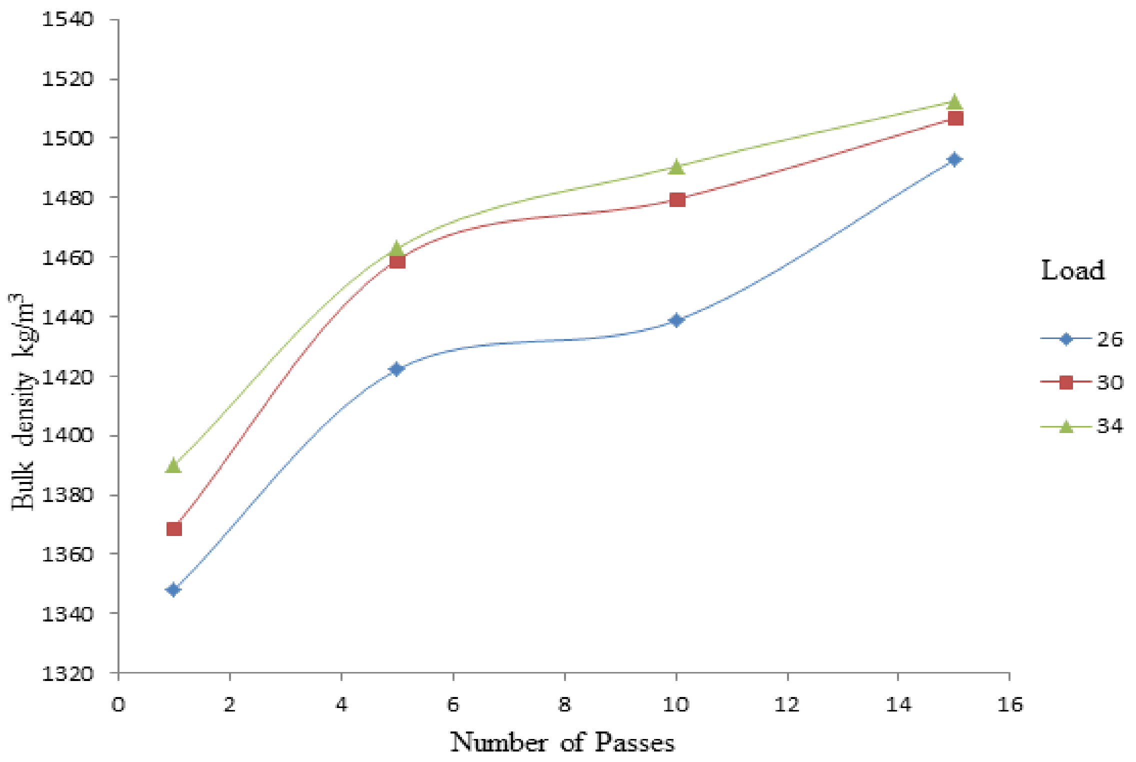


Figure 17: Effect of number of passes on Bulk density for selected loads for 0-15cm

Table 9 : Evaluation of percentage change between number of passes for 26 kN

Loading	No of passes				Percentage change in Bulk density
	1	5	10	15	
26	1348	1422			$\left\{\frac{1422-1348}{1348}\right\} \times 100 = 5.5\ \%$
26		1422	1439		$\left\{\frac{1439-1422}{1422}\right\} \times 100 = 1.2\%$
26			1439	1493	$\left\{\frac{1493-1439}{1439}\right\} \times 100 = 3.8\%$

Table 10: Evaluation of percentage change between number of passes for 30 kN

Loading	No of passes				
	1	5	10	15	Percentage change in Bulk density
30	1369	1459			$\left\{\frac{1459-1369}{1369}\right\}\times 100 = 6.6\ \%$
30		1459	1479		$\left\{\frac{1479-1459}{1459}\right\}\times 100 = 1.4\%$
30			1479	1507	$\left\{\frac{1507-1479}{1479}\right\}\times 100 = 1.9\%$

Table 11: Evaluation of percentage change between number of passes for 34 kN

Loading	No of passes				
	1	5	10	15	Percentage change in Bulk density
34	1390	1463			$\left\{\frac{1463-1390}{1390}\right\}\times 100 = 5.3\ \%$
34		1463	1490		$\left\{\frac{1490-1463}{1463}\right\}\times 100 = 1.8\%$
34			1490	1513	$\left\{\frac{1513-1490}{1490}\right\}\times 100 = 1.5\%$

4.2.2 Effect of the number of passes on bulk density for selected depths

The top soil layer has the highest bulk density and increases with increasing number of passes. The increase in bulk density between a single pass and 15 passes in the top layer is 10.8% (Table 12, 13 and 14). The second soil layer is less affected as the decrease in bulk density between first and the second layers for 1,5,10 and 15 passes are 9.9%, 10.7%, 9.7% and 6.8% respectively. From this result the top layer has the lowest bulk density of 1348 kg/m^3 and the highest is 1493 kg/m^3. The 15-30 cm, 30-45cm and 45-60 cm are less affected though there is an increase in bulk density with corresponding change in the number of passes (Figure 18). Lipec (2012) studied the effects of compaction on pore size distribution of a soil aggregate at zero, three and five number of passes. He concluded that soil compaction decreases the pore sizes with increase in the number of passes. This implies that there is a decrease in volume and an increase in bulk density of the soil. The same trend happened with the loading level of 30 kN and 34kN though with higher bulk density. There is also a general decrease in bulk density with increase in depth for the selected levels of loading. The increase in bulk density means the soil cannot allow water penetration and at the same time roots will not penetrate deeper. Due to high bulk density increase in surface runoff will results and poor yields (Ramazan, 2012) in his study established that soil compaction affects the length of crop roots and yield of corn under irrigation.

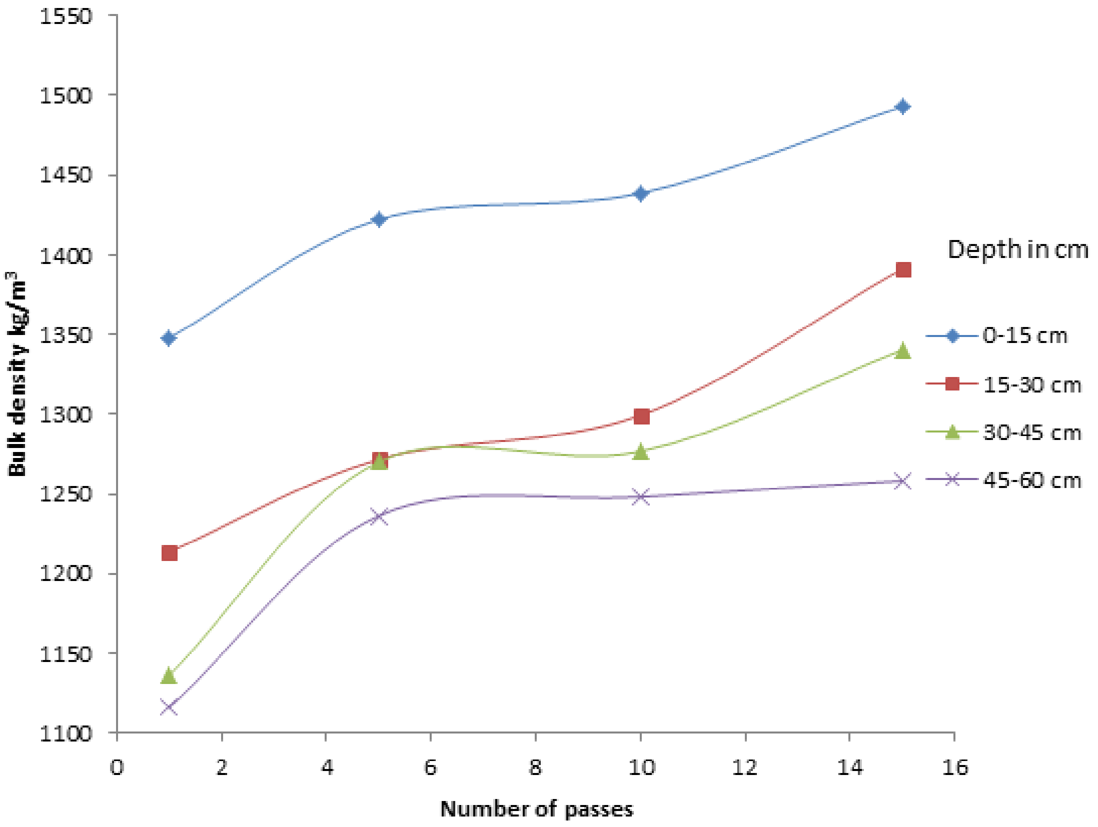


Figure 18: Effect of number of passes on Bulk density for selected depths for a loading of 26kN.

Table 12: Evaluation of percentage change between number of passes for 15-30cm depth

Loading	No of passes				
	1	5	10	15	Percentage change in Bulk density
15-30cm	1214	1272			$\left\{\frac{1272-1214}{1214}\right\} \times 100 \ = 4.8\ \%$
15-30cm		1272	1299		$\left\{\frac{1299-1272}{1272}\right\} \times 100 \ = 2.1\ \%$
15-30cm			1299	1391	$\left\{\frac{1391-1299}{1299}\right\} \times 100 \ = 7.1\ \%$

Table 13: Evaluation of percentage change between number of passes for 30-45cm depth

Loading	No of passes				Percentage change in Bulk density
	1	5	10	15	
30-45cm	1136	1270			$\left\{\frac{1270-1136}{1136}\right\} \times 100 = 11.8\ \%$
30-45cm		1270	1277		$\left\{\frac{1277-1270}{1270}\right\} \times 100 = 0.6\ \%$
30-45cm			1277	1340	$\left\{\frac{1340-1277}{1277}\right\} \times 100 = 4.9\ \%$

Table 14 : Evaluation of percentage change between number of passes for 45-60cm depth

Loading	No of passes				Percentage change in Bulk density
	1	5	10	15	
45-60cm	1116	1236			$\left\{\frac{1236-1116}{1116}\right\} \times 100 = 10.8\ \%$
45-60cm		1236	1248		$\left\{\frac{1248-1236}{1236}\right\} \times 100 = 1.0\ \%$
45-60cm			1248	1258	$\left\{\frac{1258-1248}{1248}\right\} \times 100 = 0.8\ \%$

4.2.3 Effect of loading on bulk density for selected number of passes

The bulk density for a single pass displays a linear relationship (Figure 19) and has the lowest bulk density ranging from 1348 kg/m^3 to 1390 kg/m^3 because it was ploughed and harrowed in preparation for planting, hence had no effects of the previous farm operations. The above relationships show that loading affects bulk density and increases with the increase in loading. The change in bulk density for a loading level of 26kN from one pass to five passes is 5.5% as indicated in table 9. The results clearly indicates that with a single pass the soil is far much less compacted or affected as compared to subsequent repeated number of passes.

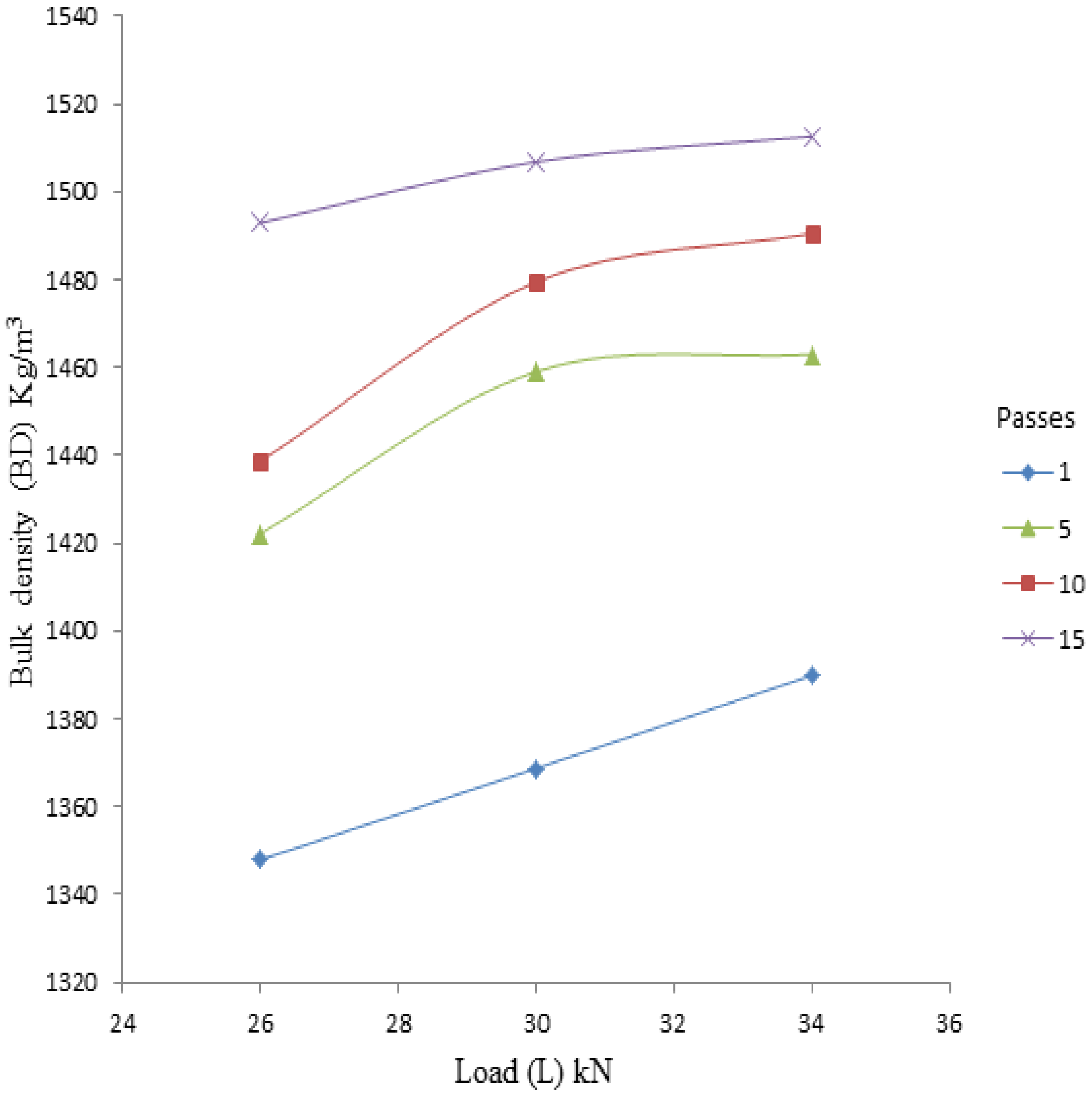


Figure 19: Effect of loading on bulk density for selected number of passes for 0-15cm layer

4.3 Effects of loading and number of passes on penetration resistance

4.3.1 The 0-15 cm soil layer with varying loading level

The top soil layer which is normally affected by all farm operation(Figure 20) is least affected and it has the initial penetration resistance of 9.52 J/cm for one pass, 16.24 J/cm for 15 number of passes an increase of 70.6 % for a loading level of 26 kN. The penetration resistance increases with increase in loading. It also increases with the increase in the number of passes. The 22.08 J/cm is the highest penetration resistance for the highest loading and number of passes for this layer.

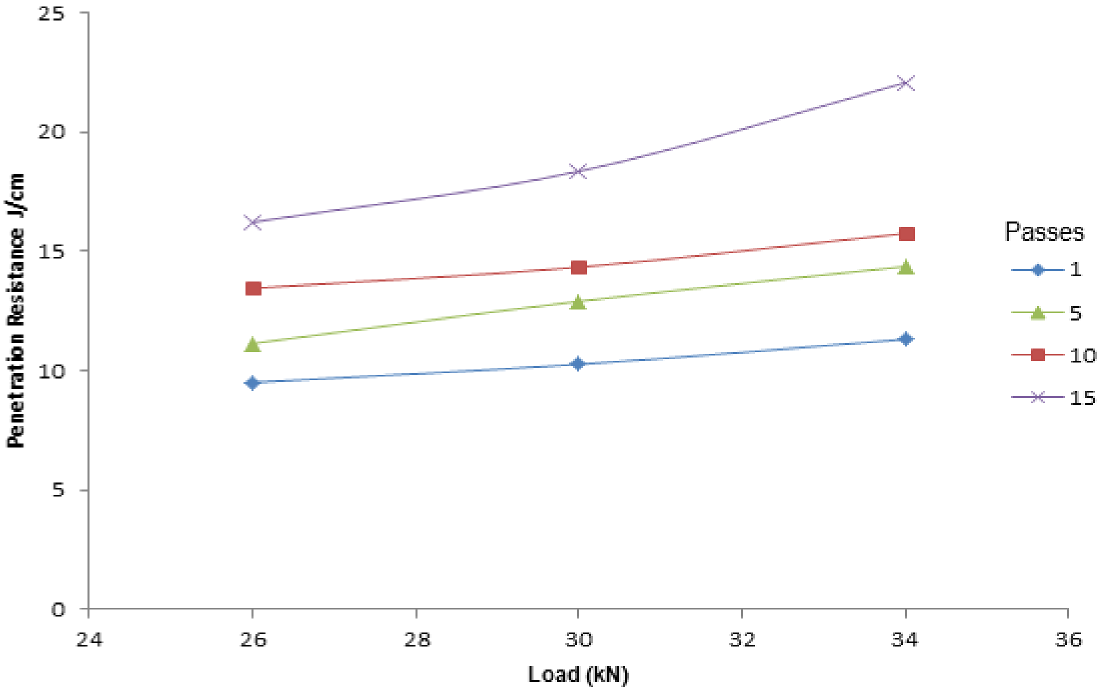


Figure 20: Effect of loading on PR for selected number of passes for 0-15 cm soil layer

4.3.2 Effects of the Number of Passes on Penetration Resistance for selected depths and various loading.

The effects of the number of passes as depicted by figure 21 clearly show that the highest number of passes has a higher impact on the penetration resistance as opposed to the single pass. For a single pass the Penetration resistance on the 45 – 60 cm layer was found to be 15.86 J/cm and 42.41 J/cm for 15 passes. The highest number of passes affects all the selected soil layers. This means that as you increase the number of passes the impact on the soil goes deeper into the soil. The same trend applies to all the other loading levels of 30 kN and 34 kN (Figure 28 and 29)

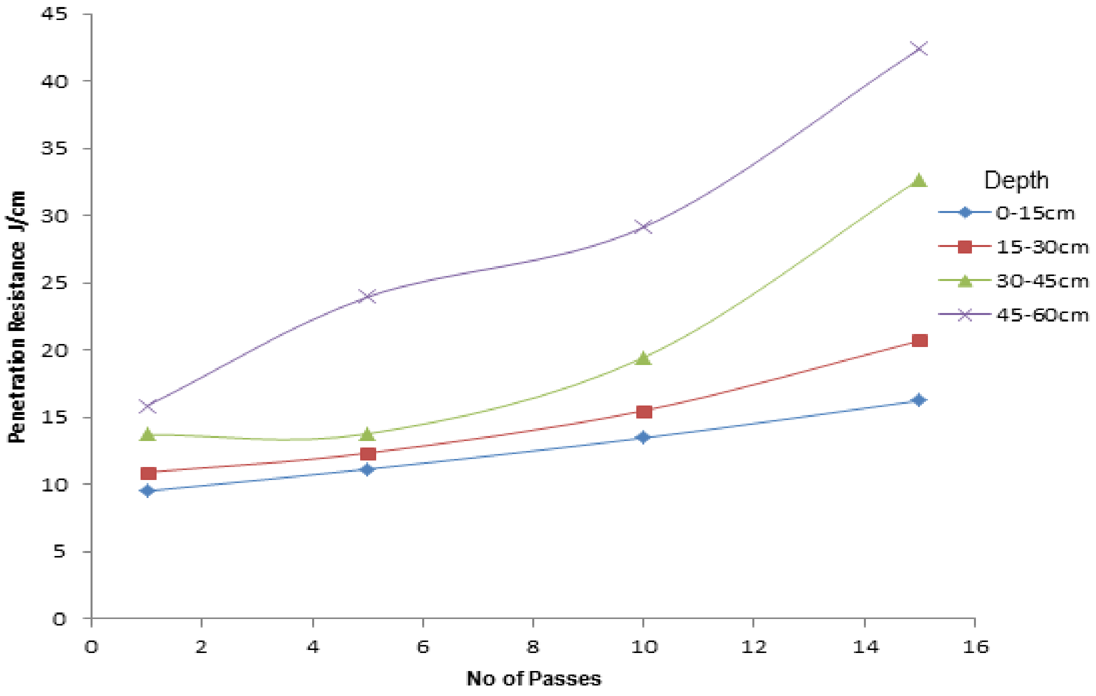


Figure 21: Effects of the Number of passes on PR for selected depth range and a loading of 26 kN

4.3.3 Effect of number of passes on PR on 0-15 cm soil layer with selected load

The number of passes and selected loads show increase in penetration resistance with increase in the number of passes. There is also vertical increase in penetration resistance due to increase in loading (Figure 22). For a single pass at a loading of 26 kN the PR is 9.52 J/cm and the same at a loading of 34 kN the PR is 11.33 kN which is an increase of 19%. The penetration resistance for 15 passes at 26 kN is 16.24 J/cm and for 15 passes at 34 kN is 22.08 J/cm reflecting an increase of 36%. Considering the change in in terms of number of passes for one pass and 15 passes at 26 kN the increase is 70.6 %, same for a loading level of 30 kN is 79 % and for 34 kN is 95 %. Similar trends can be seen for all the other layers but at different percentage increase.

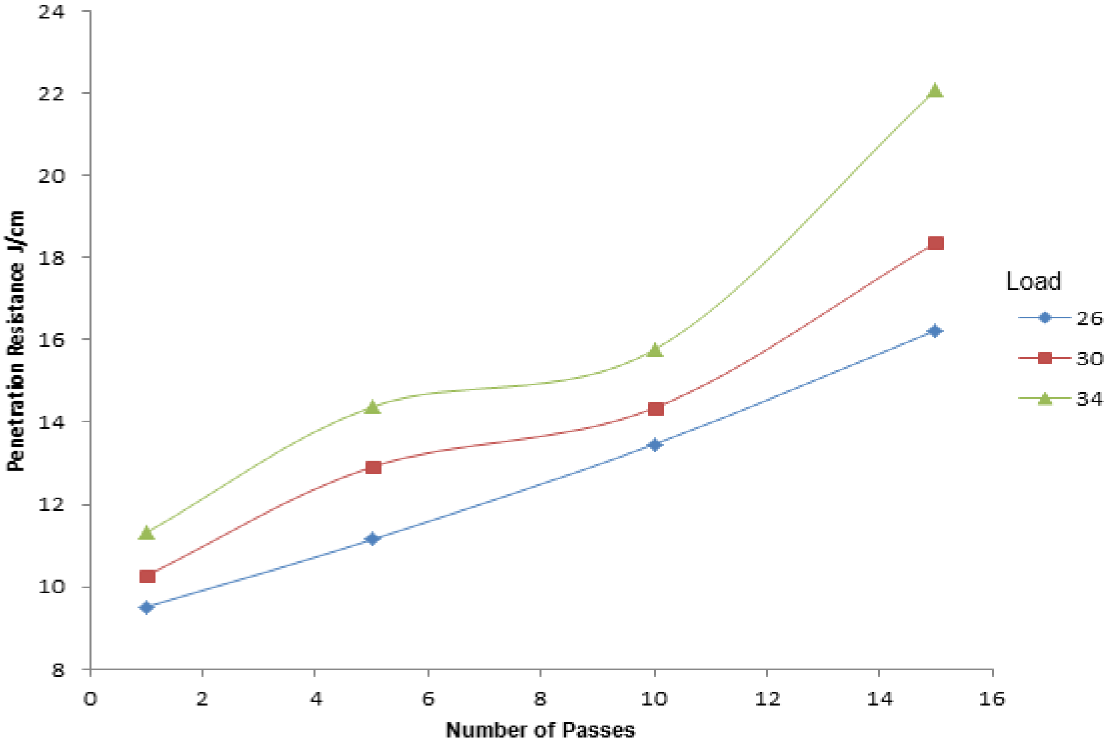


Figure 22: Effect of number of passes on PR for selected loads for 0-15cm soil layer

4.4 Analysis of variance for Bulk density

The multiple regression analysis of variance for bulk density was done using stepwise method (Minitab software), at 99% confidence interval and the P-value of $\alpha = 0.01$. The results are displayed on the ANOVA table (Table 15). The load, number of passes and depth are all significant at 95% confidence level

Table 15: Analysis of Variance (ANOVA) for bulk density

Source	DF	SS	MS	F-Value	P-Value
L	2	41937	20968	32.23*	0.00
D	3	243962	81321	125.00*	0.00
P	3	221147	73716	113.31*	0.00
Error	39	25372	651		
Total	47	532417			

*Significant at 5%

Coefficient of determination (R^2) is 95.23%

4.4.1 Bulk density regression equation

Regression Equation for predicting the bulk density at a given depth, loads and number of passes was developed using Minitab software by stepwise method and the final equation is given by equation 4.1.

$$BD = 1094.6 + 9.02\,L - 4.099\,D + 12.03P \qquad \text{Eqn (4.1)}$$

Where BD - Bulk density (kg/m^3), D - Depth (cm), L - Load (kN) and P – Passes

Using Principal component analysis(PCA) method in excel it was established that in equation 4.1 the final bulk density consist of 0.48 proportion of loading, 0.25 proportion number of passes and finally 0.25 proportion of depth(Table 16). The results show that the loading has the highest impact on the bulk density and contributes 48.3% to soil compaction while the number of passes and depth contribute 25% each. This confirms that axle load is the main cause of sub soil compaction as compared to the number of passes.

Table 16: Principal component analysis for bulk density

	L	D	P	BD
Variance	1.93	1.00	1.00	0.07
Proportion	0.48	0.25	0.25	0.02
Cumulative Proportion	48.3%	73.3%	98.3%	100.0%

The model regression equation was used to predict bulk density and compared graphically with the measured results of bulk density (Figure 23). The coefficient of determination R^2 is 0.8822 for linear correlation. If the intercept is selected to pass the origin (x=0, y=0) the coefficient of determination R^2 drops to 0.8624. The best line therefore is the one with the intercept of 1912.5 returns the highest R^2 of 0.8822. The results display a second degree polynomial relationship between the observed and predicted results.

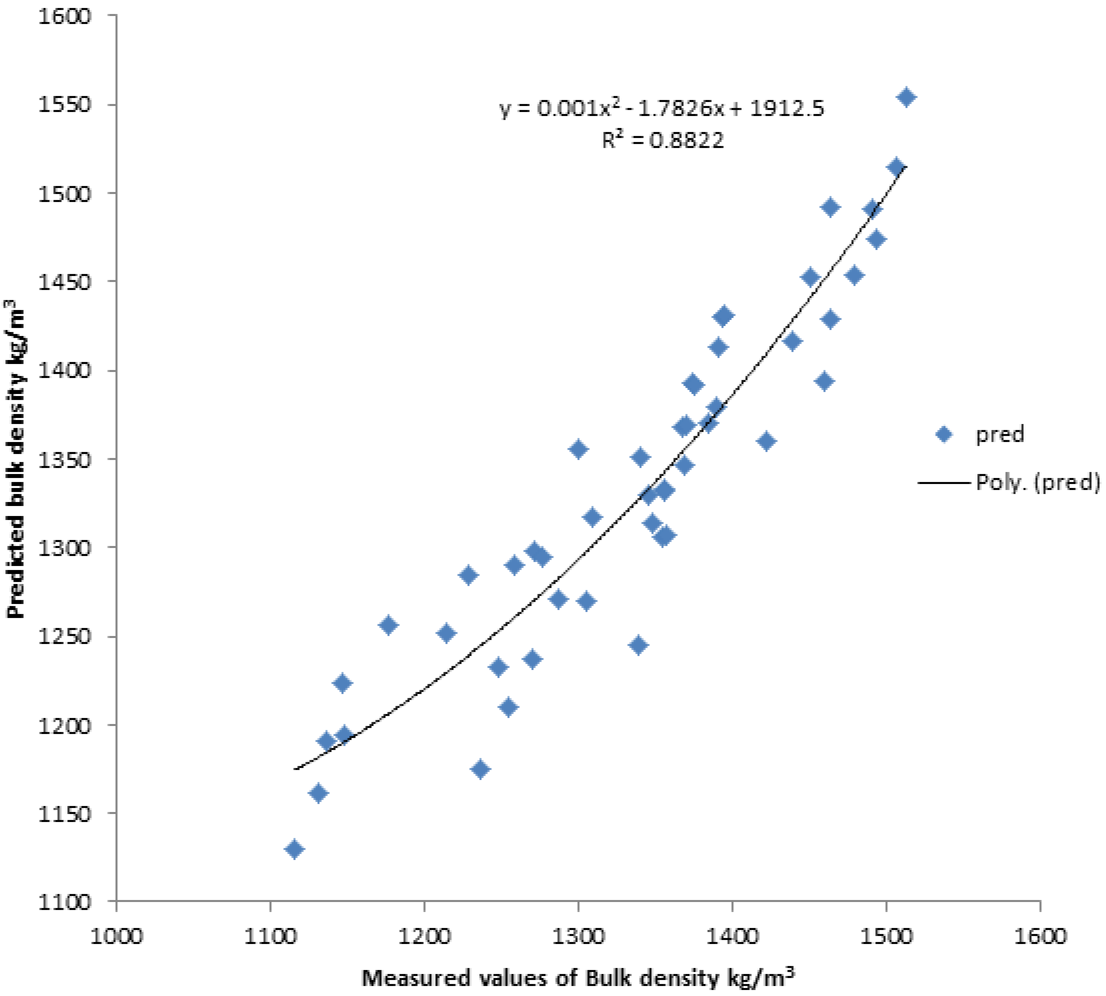


Figure 23: The relationship of observed against the predicted results of bulk density

4.5 Analysis of variance for Penetration Resistance

The multiple regression analysis of variance for penetration resistance was done using stepwise method and at 95% confidence interval and the P-value of $\alpha = 0.05$. The results are displayed on the ANOVA table (Table 17).The evaluated results shows that the load, depth and number of passes are all significant at 95% confidence level. The regression equation coefficient of determination (R^2) was 0.8140.

Table 17: Analysis of Variance (ANOVA) for penetration resistance

Source	DF	SS	MS	F	P
D	3	3218.84	1072.95	40.05*	0.000
L	2	598.59	299.30	11.17*	0.000
P	3	755.07	251.69	9.40**	0.000
Error	39	1044.72	26.79		
Total	47	5617.23			

*Significant at 5%

**Significant at 1%

Coefficient of determination $R^2 = 0.8140$

4.5.1 Penetration resistance analysis regression equation.

The penetration resistance regression equation was developed based on the loading, number of passes and depth. The proposed regression equation for the prediction of penetration resistance at any given depth, load and number of passes is given by Equation 4.2

$$PR = 1.079\,L + 0.4798\,D + 0.733\,P - 29.16 \qquad \text{Eqn (4.2)}$$

Where PR - Penetration resistance (J/cm), D - Depth (Cm), L - Load (kN) and P – Passes.

The proposed regression equation 4.2 was used to predict the penetration resistance compared graphically with measured results Figure 24, the coefficient of determination (R^2) when the intercept is taken to the origin (x=0, y=0) is 0.7389 while in the case where there is an intercept the coefficient of determination R^2 is 0.8674. The fitted line is a second degree polynomial correlation with the highest coefficient of determination.

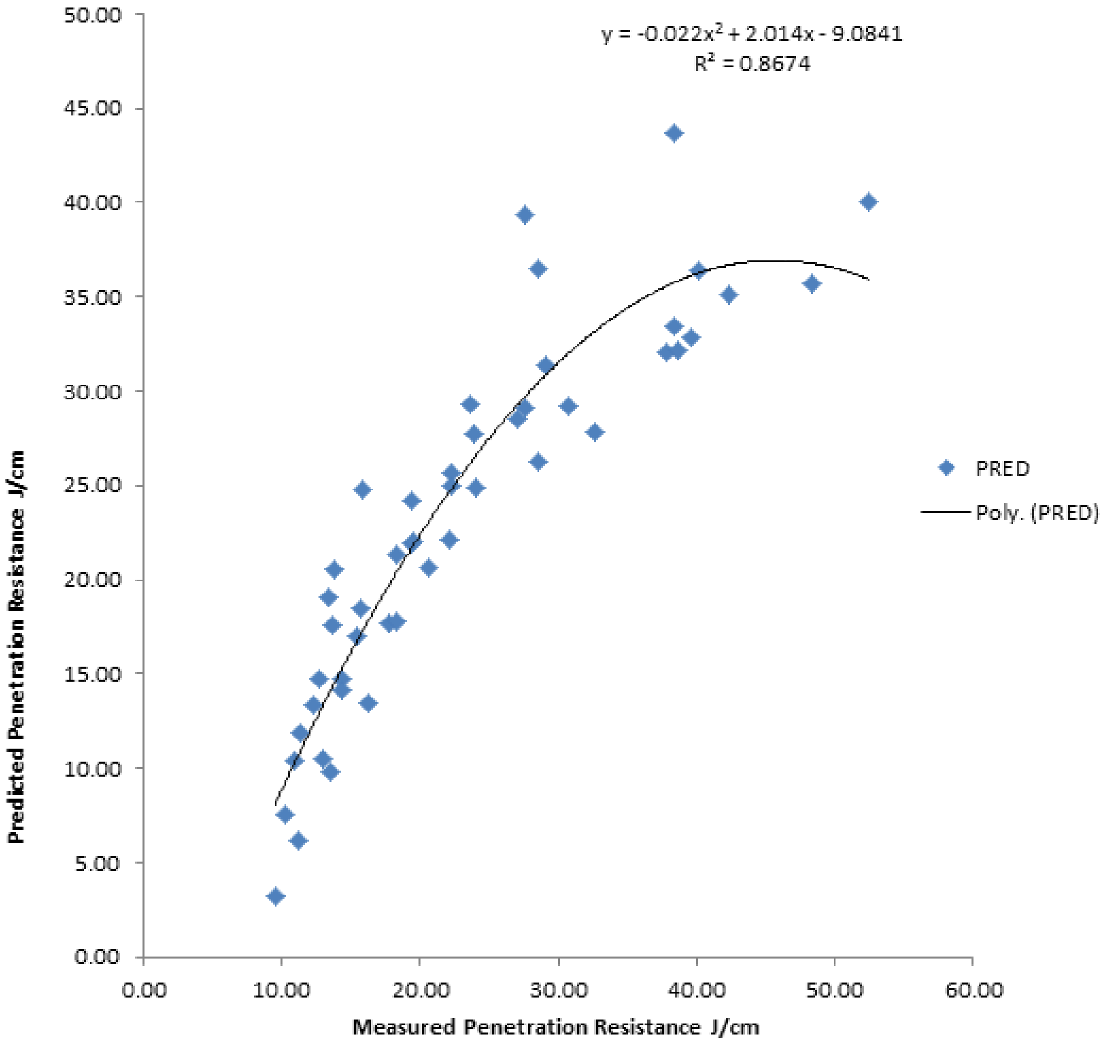


Figure 24: Measured Penetration Resistance against predicted Penetration resistance graph

Using Principal component analysis (PCA) method it was established that in equation 4.2 the final penetration resistance consist of 0.46 proportion of loading, 0.25 proportion numbers of passes and finally 0.25 proportion of depth (Table 18). The results show that the loading has the highest impact on the penetration resistance and contributes 46% to soil compaction while the number of passes and depth contribute 25% each.

Table 18: Principal component analysis for penetration resistance

	L	D	P	PR
Variance	1.84	1.00	1.00	0.16
Proportion	0.46	0.25	0.25	0.04
Cum. Proportion	46.1%	71.1%	96.1%	100.0%

4.6 Bulk density for 30-45cm with a fitted line

The results of soil layer 30-45cm displayed graphically displays a second degree polynomial relationship with the coefficient of determination of 0.8985 and 0.9243 for 26kN and 30kN test results (Figure 25)

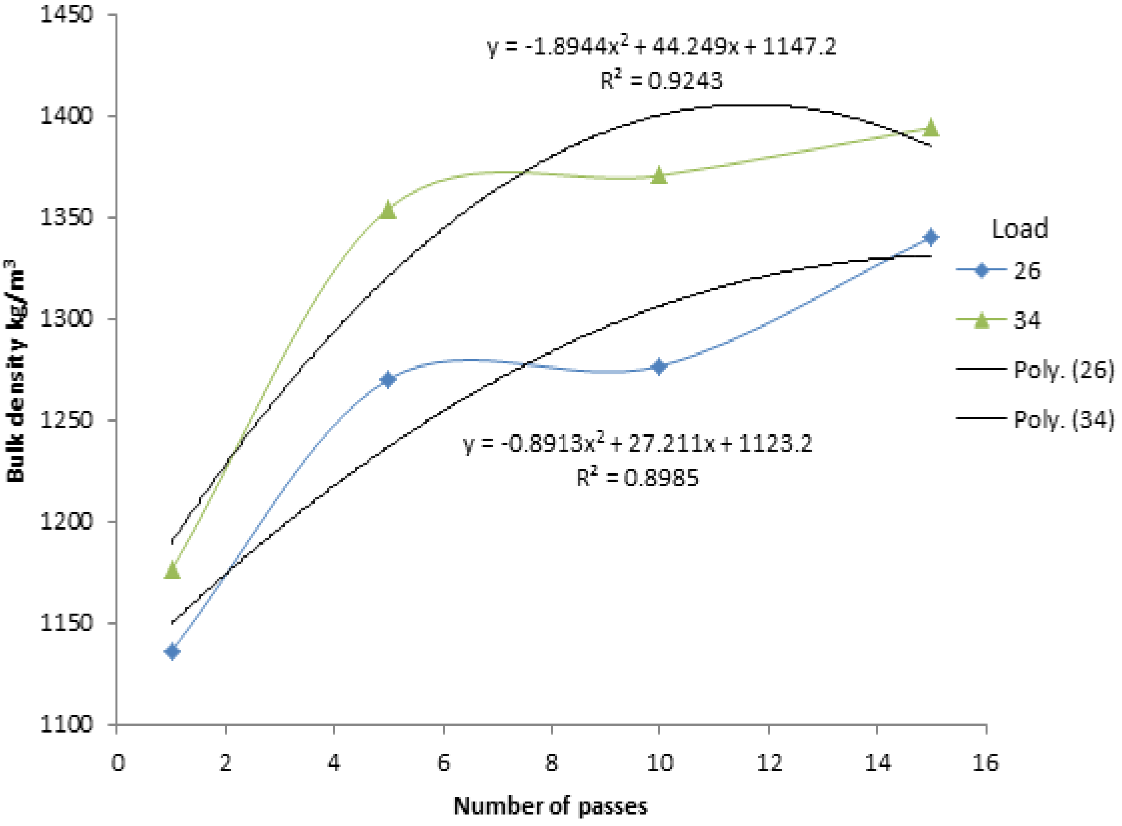


Figure 25: Fitted lines to measured results of bulk density for 26 kN and 34 kN

4.7 Penetration resistance for 30-45cm with a fitted line

The results of soil layer 30-45cm displayed graphically displays a second degree polynomial relationship with the coefficient of determination of 0.9997 and 0.9891for 26kN and 30kN test results (Figure 26)

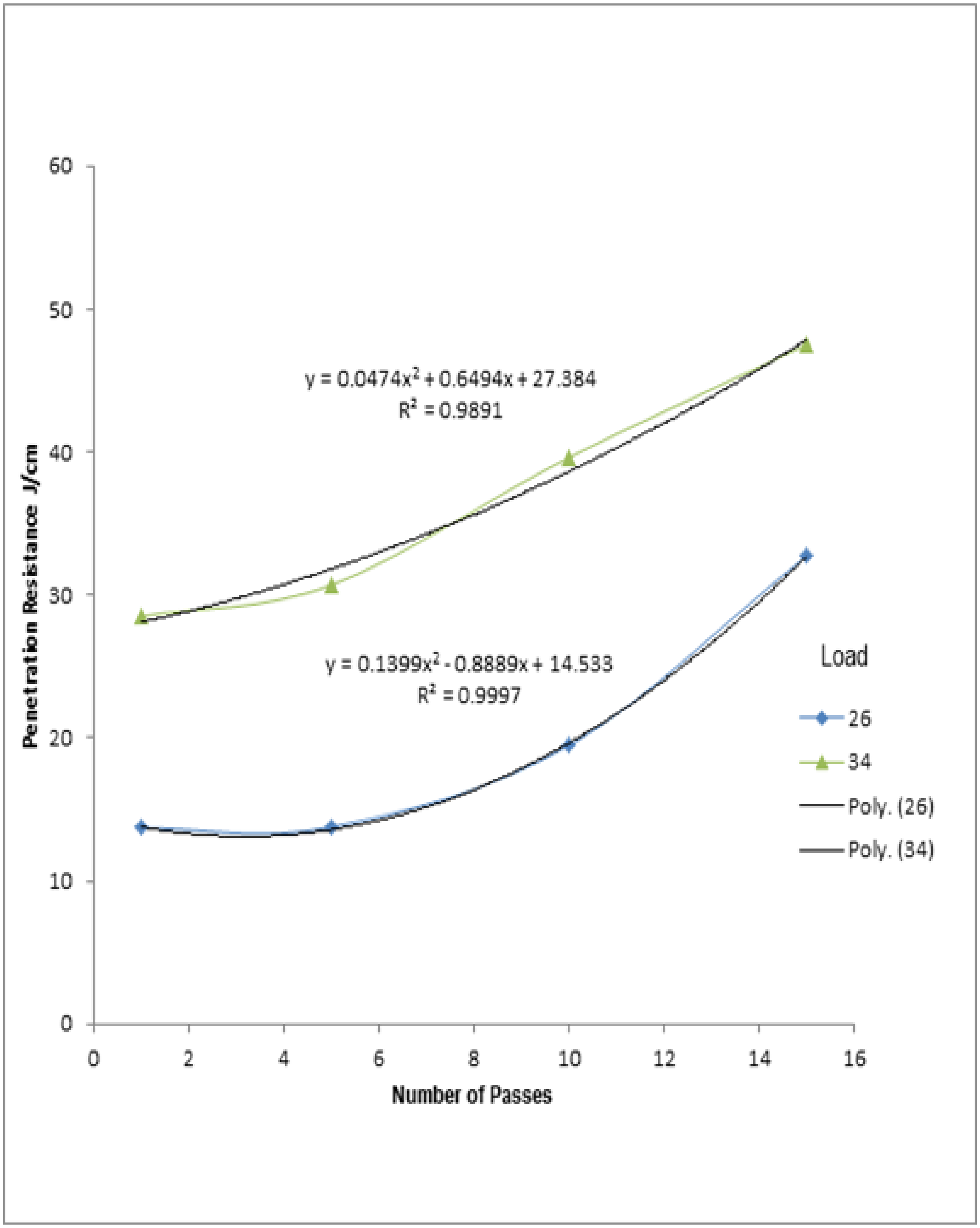


Figure 26: Fitted lines measured results of Penetration resistance for 26 kN and 34 kN

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

The maximum dry density (MDD) was 1376 kg/m^3.Observed bulk density 1116 to 1513 kg/m^3 and the Relative compaction was 81.1% to 110%

i. The effect of loading on bulk density on the top soil layer was high and it decreased with the increase in depth.

ii. Bulk density increased with the increase in the number of passes.

iii. Loading and the number of passes were found to have a significant impact on penetration resistance.

iv. The increase in loading has more effect on the lower layers of the soil than the number of passes.

v. The coefficients of determination (R^2) for bulk density and penetration resistance were found to be of 0.8822 and 0.8674, respectively.

5.2 Recommendation

i) During farm operations the plant operators should be trained to minimize the number of runs on the same tyre track.

ii) The study also revealed that the increase in axle load causes the highest impact on the soil and affects even the subsoil; therefore unnecessary increase on the axle loading on the machinery should be avoided where possible.

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APPENDICES

Appendix I: Bulk density data

Table 19: Bulk density kg/m^3 with changing normal load and number of passes in the 0-15cm soil layer

Loading (kN)	Number of Passes			
	1	5	10	15
26	1348	1422	1439	1493
30	1369	1459	1479	1507
34	1390	1463	1490	1513

Table 20: Bulk density kg/m^3 with changing normal load and varying number of passes in the 15-30 cm soil layer

Loading (kN)	Number of Passes			
	1	5	10	15
26	1214	1272	1299	1391
30	1228	1356	1374	1450
34	1309	1367	1394	1463

Table 21: Bulk density kg/m^3 with changing normal load and varying number of passes in the 30-45cm soil layer

Loading (kN)	Number of Passes			
	1	5	10	15
26	1136	1270	1277	1340
30	1147	1287	1356	1375
34	1176	1354	1371	1394

Table 22: Bulk density kg/m^3 with changing normal load and number of passes in the 45-60 cm soil layer

Loading (kN)	Number of Passes			
	1	5	10	15
26	1116	1236	1248	1258
30	1131	1255	1305	1345
34	1147	1339	1357	1385

Table 23: Variation in Bulk density with soil depth at varying number of passes at 26 kN normal loading

Depth (cm)	Number of Passes			
	1	5	10	15
7.5	1348	1422	1439	1493
22.5	1214	1272	1299	1391
37.5	1136	1270	1277	1340
52.5	1116	1236	1248	1258

Table 24: Variation in Bulk density with soil depth at varying number of passes at 30 kN normal loading

Depth (cm)	Number of Passes			
	1	5	10	15
7.5	1369	1459	1479	1507
22.5	1228	1356	1374	1450
37.5	1147	1287	1356	1375
52.5	1131	1255	1305	1345

Table 25: Variation in Bulk density with soil depth at varying number of passes at 34 kN normal loading

Depth (cm)	Number of Passes			
	1	5	10	15
7.5	1390	1463	1490	1513
22.5	1309	1367	1394	1463
37.5	1176	1354	1371	1394
52.5	1147	1339	1357	1385

Appendix II: Penetration resistance data

Table 26: Variation in Penetration resistance J/cm with depth at varying number of passes at a normal load of 26 kN

Depth (cm)	Number of passes			
	1	5	10	15
7.5	9.52	11.15	13.47	16.24
22.5	10.91	12.35	15.50	20.70
37.5	13.71	13.77	19.46	32.72
52.5	15.86	23.94	29.14	42.41

Table 27: Variation in Penetration resistance J/cm with depth at varying number of passes at a normal load of 30 kN

Depth (cm)	Number of Passes			
	1	5	10	15
7.5	10.28	12.92	14.35	18.37
22.5	12.78	17.83	18.27	22.31
37.5	19.45	24.03	27.00	38.69
52.5	27.63	37.79	48.42	48.98

Table 28: **Variation in Penetration resistance J/cm with depth at varying number of passes at a normal load of 34 kN**

Depth(cm)	Penetration resistance J/cm			
	1	5	10	15
7.5	11.33	14.38	15.77	22.08
22.5	13.40	19.52	22.21	23.62
37.5	28.52	30.71	39.60	47.48
52.5	38.34	40.11	52.50	54.12

Table 29: Variation in Penetration resistance J/cm with load at varying number of passes for 0-15 cm layer

Load(KN)	Number of passes			
	1	5	10	15
26	9.52	11.15	13.47	16.24
30	10.28	12.92	14.35	18.37
34	11.33	14.38	15.77	22.08

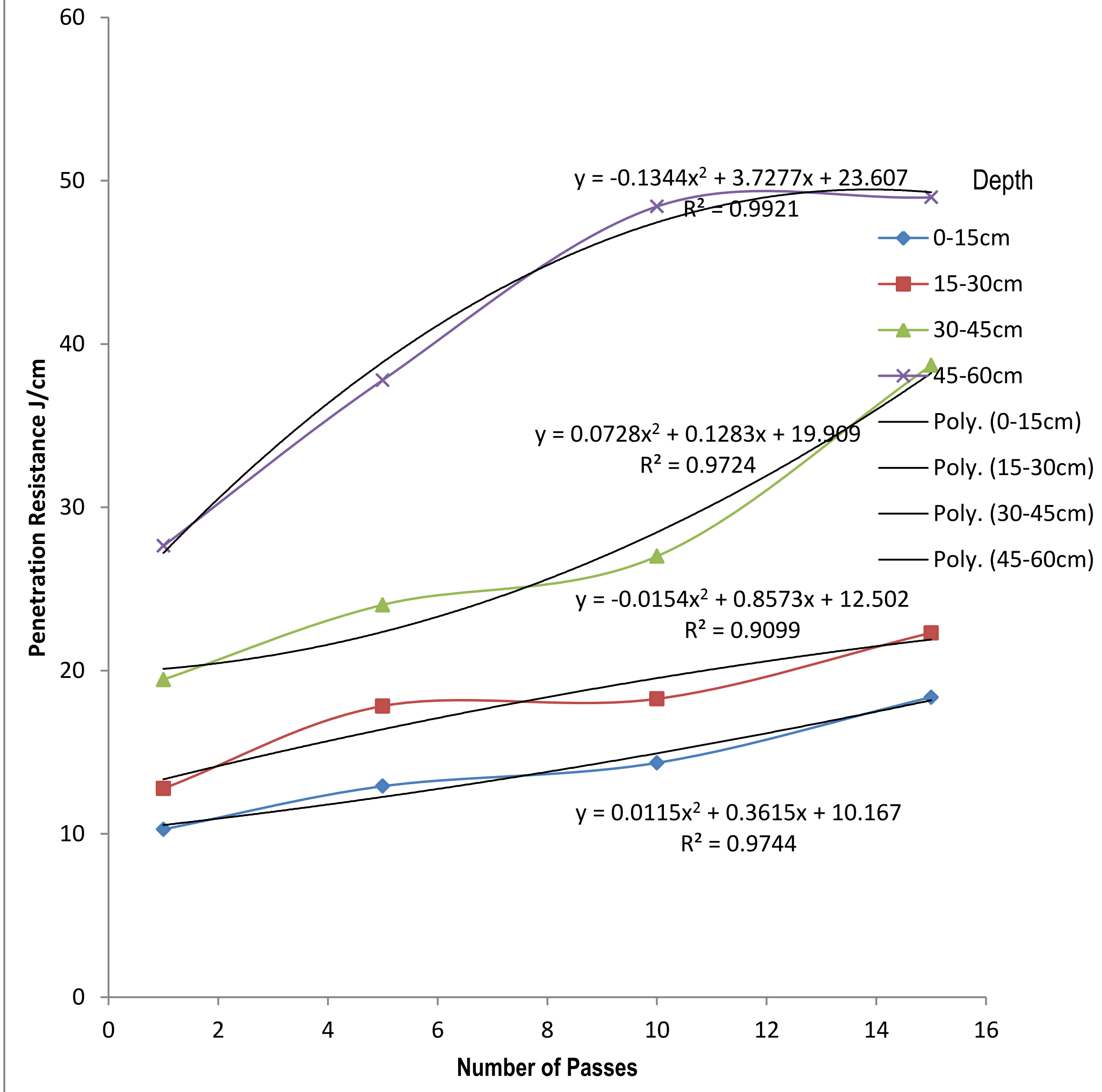

Figure 27: **Effects of number of passes on Penetration resistance for selected loading of 30kN**

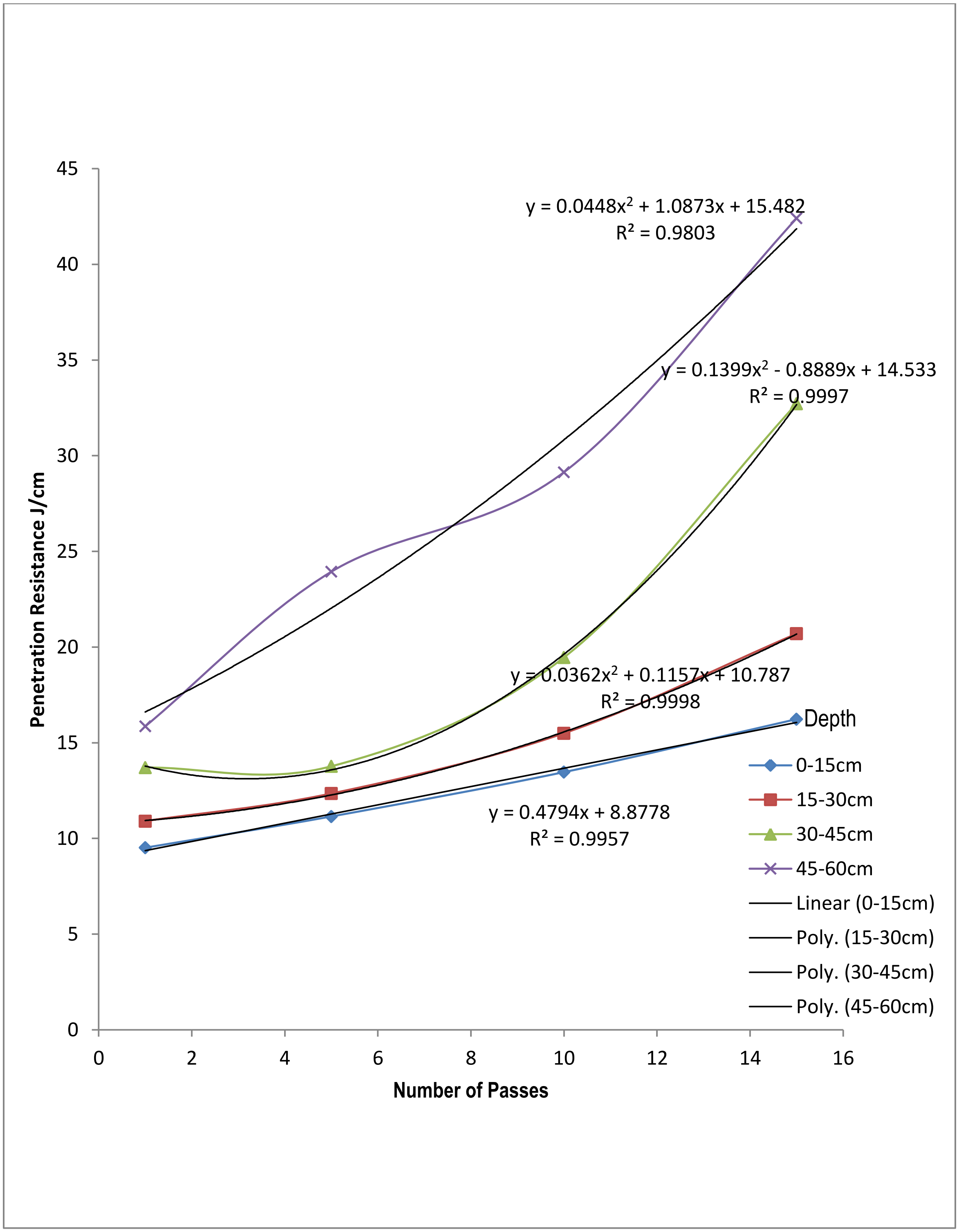

Figure 28: Effects of loading on Penetration resistance for selected depths for a loading of 34 kN .

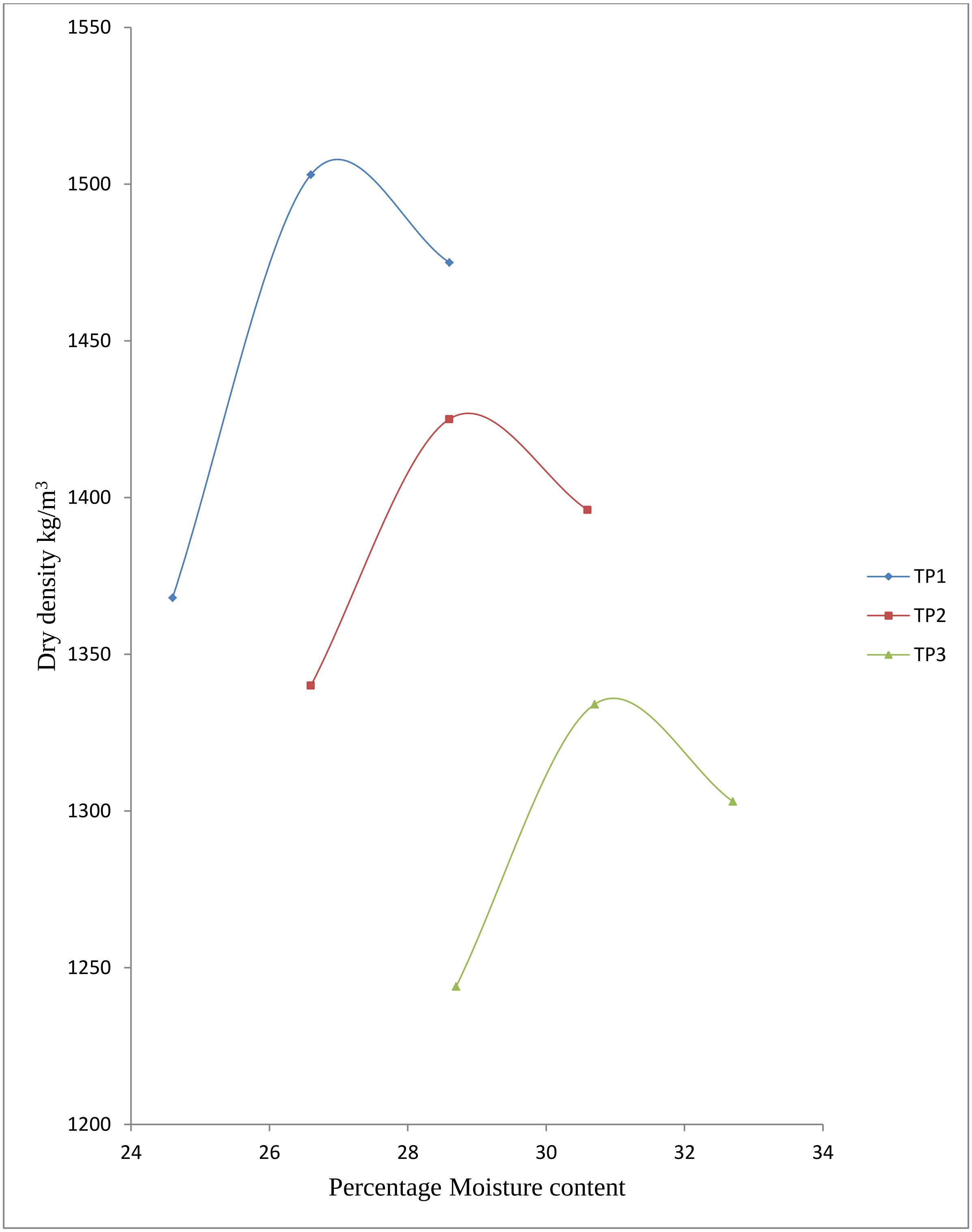

Figure 29: A graph of moisture content % against dry density kg/m^3

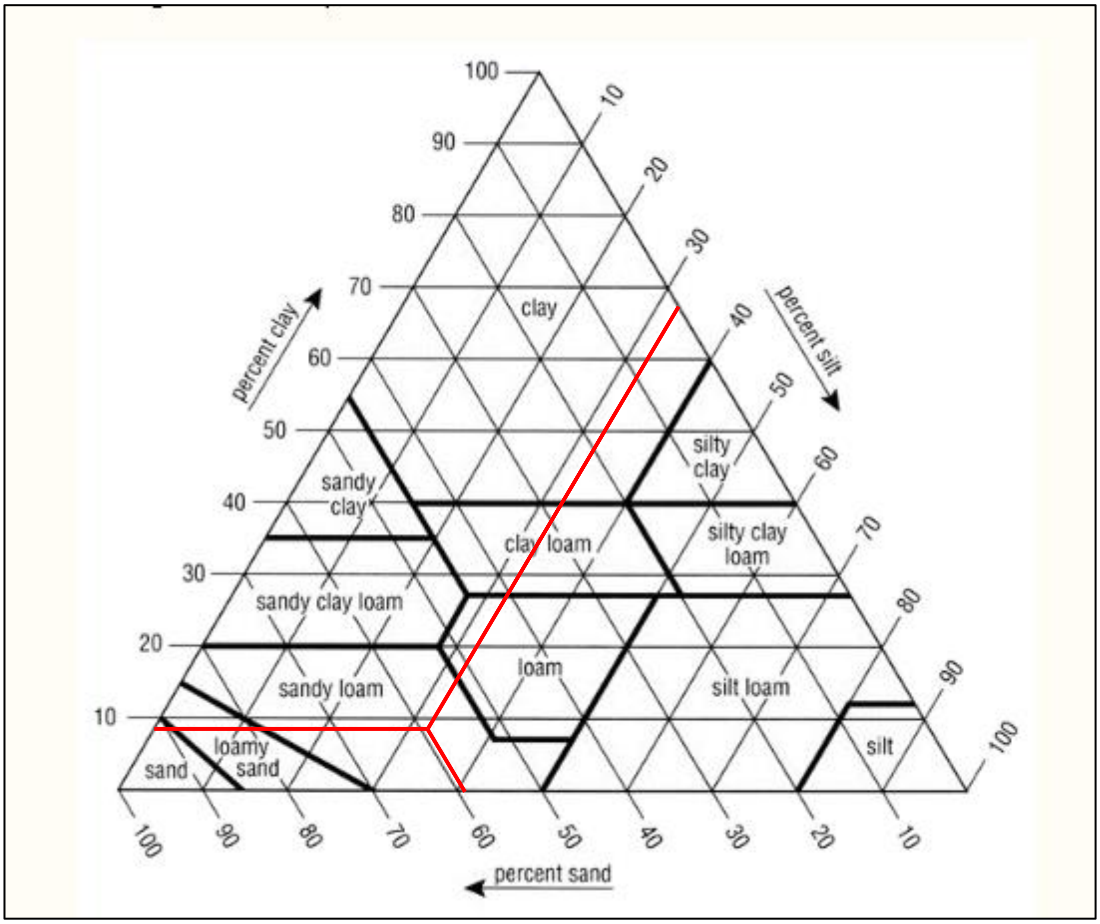

Figure 30: USDA Soil Textural triangle

(Source : Hillel, 1980)

Figure 31: One of the heavy farm machinery used in the farm

(Source : Author, 2015)