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DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

Optimisation of Specific Draft Requirement and Hitch Length for an Animal-drawn Sub-Soiler: A Case Study of Sandy Clay Loam Soils

By

NICODEMUS KYALO MWONGA

F56/70183/2011

(B.Sc. Hons Agric. Eng. (1990), Egerton University)

A thesis submitted to the Department of Environmental and Biosystems Engineering, University of Nairobi, in partial fulfilment of the requirements for the Degree of Master of Science in Environmental and Biosystems Engineering

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SUPERVISORS

This thesis has been submitted for examination with our approval as supervisors.

……………………………… ………………………

Ayub. N. Gitau, PhD **Date**

Department of Environmental & Biosystems Engineering

University of Nairobi

……………………………… ………………………

Joackim M. Mutua, MSc **Date**

Department of Environmental & Biosystems Engineering

University of Nairobi

DECLARATION OF ORIGINALITY

Name of Student:	Nicodemus Kyalo Mwonga
Registration:	F56/70183/2011
College:	Architecture and Engineering
Faculty/School/Institute:	Engineering
Department:	Environmental and Biosystems Engineering
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DEDICATION

I wish to dedicate this work to my dear sister Mrs Beatrice Ndambuki who educated me. My niece Dr. Catherine Ndinda for her encouragement and financial support. This work is also dedicated to my dear wife Mrs. Rose Mulee Kyalo, my three sons Leakey Kyalo, Brian Mwonga and Kevin Waki for their consistent support during the research and thesis write up.

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ABSTRACT

Land degradation is occurring very rapidly in agricultural lands in Kenya. In ASAL regions, soil compaction and poor tillage practiced has resulted in increased cost of tillage, lack of timeliness and decreased agricultural production. The objective of this study was to optimize tillage depth and hitching length for optimal draft requirement in sandy clay loam soils. Parameters pertinent to draft requirement for subsoiling were identified.

Field experiments were conducted to collect soil resistance datasets. Draft data was measured using the MSI 7300 digital dynamometer communicating remotely with data logger MSI -8000 RF logging data directly to a laptop through the serial port. The sub soiler tine tested was attached to a tool carriage attached to the oxen using a chain. The dynamometer was attached between the tool carrier and the oxen via steel shackles. For a specified speed, three hitch lengths (L_1, L_2 and L_3) and three depths (D_1, D_2 and D_3) were used in combination. Depth was measured as the vertical distance from the top of the undisturbed soil surface to the equipment deepest penetration depth and was varied from 0cm to 30cm with a range of 10cm interval. For each set up, three replications were performed giving a total of 27 treatments for each experimental site. Specific draft was evaluated at varying depth of 0-10cm, 10-20cm and 20-30 cm and varying hitching length of 2.5m, 3.0m and 3.5m for each depth. The soil-resistance datasets obtained from the field tests were compared using statistical measures of fit particularly the coefficient of determination (R^2) and the student t-test.

At the experimental fields, the bulk density varied from 1.52 to 1.37g/cm^3 and 1.44 to 1.67g/cm^3 for Machakos and Kitui sites respectively. The moisture content increased with increase in depth at the two experimental sites ranging from 3.53 to 9.94% for Machakos site and from 4.15 to 9.61% for Kitui site Soil shear strength parameters ranged between 21.71 and 29.6kPa between depths of 0-20cm and then decreased to 28.07kPa for Machakos experimental site. In Kitui experimental site, shear strength parameters ranged between 30.02 and 39.29kPa between depths of 0 and 30cm. The relationship obtained between specific draft and depth at particular hitching length as well as specific draft against hitching length is a second order quadratic model of the form $y = ax^2 + bx + c$.

Currently majority of farmers in ASAL where Animal draft power is used extensively, the hitch length used is 2.5 m. However, from this study the optimal hitching length and tillage depth for Machakos experimental site was obtained as 2.9m (~3m) and 16.5 cm respectively. In Kitui experimental site, the optimal hitching length was obtained as 2.9 m (~3m) and the optimal tillage depth was 15.4 cm.

In conclusion, this study has established that, for an animal drawn subsoiler, the optimal hitch length is 3m, which generates an optimal tillage depth in the range between 15 cm and 17cm at a minimum specific draft ranging between 32 to 35kN/m^2 and 44 to 48 kN/m^2 respectively in a sandy clay loam soils.

Key Words: *Soil resistance; optimal specific draft; hitching length; subsoiling depth; Animal draft power, Optimal hitching length, Optimal subsoiling depth, Agricultural mechanization, Kenya.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF ABBREVIATION

ADP	Animal Draught Power
ASAL	Arid and Semi-Arid Land
Cc	Coefficient of Gradation
Cu	Uniformity of Coefficient
DRSLP	Drought Resilience and Sustainable Livelihood Programme
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
ILCA	International Livestock Centre for Africa
L	Length
MoAF&I	Ministry of Agriculture, Livestock, Fisheries and Irrigation
MSc	Master of Science
R	Coefficient of Determination
SED	Standard Error of Difference
SDG	Sustainable Development Goals
SIVAP	Small Scale Irrigation and Value Addition Project
SSA	Sub-Saharan Africa
SSR	Sum of Squares by Regression
SST	Total Sum of Squares
USCS	Unified Soil Classification System

CHAPTER ONE: INTRODUCTION

1.1 Preamble

In this chapter, the foundation to the problem is discussed to orientate the reader towards the rationale for such a study. The problem statement is then illustrated and sub-problems filtered out. In addition, the objectives and the scope are outlined to give some thought with respect to the milestones to be accomplished.

1.2 Study Background

Agriculture plays a crucial role in the economy of developing Countries and provides the main source of food, income and employment to their rural populations. According to FAO (2000), it has been established that the share of the agricultural population in the total populace is 67% that agriculture accounts for 39.4% of the GDP and 43% of all exports consists of agricultural goods. It has become increasingly evident in the last few years that the conception of both economist and policy- makers regarding the role of agriculture in economic development has undergone an important evolution. Roughly, one quarter of the Earths terrestrial surface is now under cultivation with more land converted to crop production in the 30 years after 1950 than in the previous 150 years. The growth of the sector is therefore expected to have a greater impact on a larger section of the population than any other sector. The sector is without doubt a key driver towards the realization of 10 percent economic growth annually as envisioned in the Kenya Vision 2030 and Sustainable Development Goal (SDG) No. 2 with respect to: End hunger, achieve food security and improved nutrition and promote sustainable agriculture reduction of extreme poverty and hunger. (United Nations Development Programme, 2015)

Agricultural mechanization is one of the major agricultural production inputs and a catalyst for rural development. Application of agricultural mechanization technology increases power to agriculture, largely therefore enhancing productivity of human labour. Despite agricultural mechanization being vital for agricultural production, most farming communities lack appropriate machinery and equipment to undertake their operations efficiently and effectively. Currently the use of motorized power stands at 30 percent, hand and animal draught power (ADP) at 50 percent and 20 percent respectively at National level (MoALF&I, 2015).

The relatively low level of mechanization is due to a number of challenges facing the subsector. These include; inadequate research and technology development; weak local manufacturing and distribution, and insufficient agricultural mechanization quality assurance, low level of investments in mechanization services, poor extension and technology adoption, weak institutional and legal framework. The crosscutting issues affecting agricultural mechanization include matters related to vulnerable groups, gender and youth, negative effects of environment, inappropriate land use and climate change.

Although agricultural mechanization has increased at a rate of 1.0 to 1.5% per year in the developing countries such as Kenya, draft animals still remain a major source of farm power providing nearly 50% of the agricultural power (Gitau *et al.*, 1995) in the ASAL. Animals utilized as a source of traction, include oxen and donkeys in the study area while in other parts of the world horses, mules, buffalo and cattle are used. In addition to being utilized as a source of power, these same animals provide fuel, wool, hair, off-spring and by-products, such as hides, horns, hooves and meat at the end of their working lives. The extent to which draft animals are employed in tillage might lead one to expect considerable information on guidelines for utilization, but this is not the case, particularly for sub-soiling which is a more recent conservation tillage technology that has not been fully explored especially in the ASAL.

The current farming practices in the Country have resulted to land degradation through erosion, excessive mining of soils and deforestation. On the other hand, climate change has been associated with frequent, severe and prolonged droughts and floods thereby resulting to further land degradation, low productivity and loss of livelihood.

In Kenya a larger population resides in the rural areas which is mainly ASAL and depends on Agriculture for their livelihood. These Communities have been using Animal Draught Power (ADP) for cultivation and transportation for ages. Although there has been significant improvement in achieving large ploughed areas, the yields have been low owing to use of inappropriate tools that have not mobilized the soil effectively (Guthiga *et al.*, 2007).

The performance of an animal drawn tillage tool is affected by three main factors; initial soil conditions; tool geometry; and manner of the tool movement (Fielke, 1996; Anon, 1992; and Brassington, 1987). Among the three factors, a designer has complete control over only the geometry of the tool, as initial soil condition changes from place to place and time and the animal power has limited working speed and pulling capacity.

The geometry of the tool has, therefore, received considerable emphasis in the past, in view of the fact that an ideal tillage tool should perform satisfactorily over a wide range of initial soil conditions and depth of operations (Fielke, 1996). Considering the importance of sub-soiling in view of its environmental effect on reducing soil compaction, enhancing water storage and reducing soil and water erosion and seemingly declining availability of draft animal power, it is imperative to evaluate the performance of an animal drawn sub-soiler at different hitch length and depths of tillage.

Numerous studies have concentrated on effect of depth, rake angles and speed on draft requirement while limited studies have been done on the effect of hitch length and tillage depth on draft requirement for an animal drawn equipment (Muchiri, 2012). This study evaluated the effect of varying the tillage depth and draft hitch length on draft power requirement for draft animals in the lower Eastern part of Kenya particularly in Kitui and upper parts of Machakos Counties.

1.3 Problem Statement

Kenya is a predominantly dry country with about 80% (467,200 km^2) of the total area falling under Arid and Semi-Arid Lands (ASAL). The rains are low and erratic and vary greatly both in space and time. Rainfall events are generally intense and can produce considerable runoff and soil erosion. Over the last decades, there has been a general trend of soil productivity decline on cropped land. Land degradation, including a decline in plant available moisture, reduced soil fertility and soil compaction have been identified as the factors behind this gradual decline in agricultural productivity which has immensely contributed to food insecurity in the County especially in the ASAL.

A major cause of land degradation is intensive soil preparation by hand hoe or animal /tractor drawn ploughs, which together with the removal on burning of crop residues leaves the soil exposed to climatic hazards such as rain, wind and sun (Bot *et al.*,2005). It is important to examine land preparation practices, which will improve soil and water conservation and systematically reverse land degradation trend for increased crop yields.

Currently, there is no general consensus on the use of animal draft power for land preparation. On one hand, some opinion suggest that efficient and timely land preparation can be realized only through the use of mechanization through tractorisation (Loukanov *et al,* 2005). The proponents of this hypothesis consider use of animal draft power as retardation to development.

On the other hand, others see animal power as an intermediate stage to mechanization or as a panacea to achieve agricultural progress in developing countries where ownership/access to tractors by small-scale farmers is limited more particularly in the low-income areas and areas where the farming communities are mixed farmers (Mrema and Mrema, 1993).

Over time, soil compaction has become a major problem affecting production in the ASAL regions. Extensive land tillage using traditional tools such as mould board plough coupled with shallow tillage has worsened this situation. In an effort to alleviate the hostile effects of soil compaction, subsoiling using a subsoiler is recommended (Muchiri, 2012). Subsoiling is a high-energy demanding farm operation and therefore to achieve a cost effective operation, the tillage subsoiler/ripper has to be properly adjusted and matched with appropriate prime mover (Mwangi *et al.*, 2012)

This study seeks to address insufficient on-farm draft by optimizing on the limited animal draft power through correct matching of the prime mover with the relevant equipment based on accurate prediction of draft power requirement. This may result in reduced time for the operation, less draft power requirement, reduced wear/tear and significant savings on sub-soiling costs.

1.4 Justification

Conventional tillage using oxen or tractor drawn ploughs has over the years been perceived as the indicator of farm systems modernization in developing Countries (Johansen *et al.*, 2012). This has not worked well in tropics where the temperatures are high, the rainfalls are erratic and very intensive and the soils are prone to erosion. Kitui and Machakos Counties are classified as ASAL and the community mainly small scale farmers living in these areas have for a long period used the standard oxen plough without significant change in crop production. Minimum and Conservation tillage coupled with the use of appropriate tools and equipment offers a window of opportunity to convert degraded soils into productive soils and thereby improves crop yields, reduces land degradation ultimately addressing environmental conservation concerns (Rusinamhodzi *et al*., 2011 and Giller *et al*., 2009).

Quantitative evaluation of tillage equipment performance requires a measurement of induced forces from the soil-tool interaction and a measure of soil conditions to determine when and how much change occurred in the soil (Godwin, 2007). Generally, there is limited information on quantitative descriptions of equipment performance under different soil conditions. This study gives a detailed account on the tool performance in sandy clay loam soils.

1.5 Objective

1.5.1 Overall Objective

The broad objective was to optimize specific draft requirement and hitch length for an animal-drawn sub-soiler.

1.5.2 Specific Objectives

The specific objectives of the study were;

a) Identify the soil physical characteristics at the experimental sites pertinent to sub-soiling,
b) Assess the effect of hitch length and tillage depth on specific draft requirement for sub-soiling
c) Optimize hitch length and tillage depth for optimal specific draft requirement.

1.6 Hypothesis

a) The performance (power/energy requirement) of the animal drawn sub-soiler is not affected by varying soil physical parameters.
b) Power/Energy requirement of the animal drawn sub-soiler increase with increase in hitch length.
c) Power/Energy requirement of the animal drawn sub-soiler increase with increase in depth of operation.

1.7 Scope

The study involved minimum land tillage using a sub-soiler while varying the depth of tillage at 3 levels (i.e. 0-10, 10-20 and 20-30cm) as well as three levels of hitching length (2.5, 3.0 and 3.5m) with determination of the draught forces for each depth and hitching length combination. The experimental study was conducted at two experimental sites one in Machakos County and a second site in Kitui County. The experimental plots were fairly flat with negligible slope. The depth of tillage and hitching length were varied while maintaining the speed and the soil type relatively constant. Soil parameters pertinent to subsoiling were determined through both in-situ and laboratory testing. Draft data was recorded using a MSI- 7800 digital dynamometer and transmitted remotely to a computer through a data logger MSI-8000RF. The draft forces were analysed and the optimal hitching length and tillage depth at optimal specific draft requirement were determined. Statistical analyses of the data were also performed to determine whether there was any significant difference between different tillage depths and hitching lengths for the experimental sites.

CHAPTER TWO: LITERATURE REVIEW

2.1 Preamble

This chapter describes the literature survey of the broad topic of interest regarding various mechanization technologies with a special reference to animal draft. It also presents a review of mechanization status in Kenya, draft power requirement for subsoiling, effects of subsoiling on soil properties and effect of tillage speed, depth and hitching on draft requirement. This chapter also includes literature review regarding the soil compaction, its causes and techniques available for alleviate soil compaction.

2.2 Agricultural Mechanization

2.2.1 Overview

In Africa, agricultural mechanization begun around 6500BC in Egypt where draught animals were first used in transportation and land preparation. The mules, horses, oxen and donkeys were the animals used for draught. It is believed that animal draught technologies spread to North Africa, Sudan and Mediterranean from Egypt (Starkey, 1986). Ramaswamy (1981) estimated the number of animal draft to be about 400 million while ILCA, (1981) and Anderson (1984) estimated that Africa has 10 to 17 million-draft animals.

Mathers, (1984) recommended power output and safe average draft for a pair of bullocks (Table 2.1). Performance and power output of draught animals is proportional to the weight of the animals (Gitau, 1995). The draft power requirements depend upon the soil conditions, the field operation and the type of equipment. Other researchers in the field (FAO, 1972; Crossley and Kilgour, 1983) reported similar findings

Table 2-1 Draft and Power output (as cited by Gitau, 1995).

Bullock Pair Weight (kg)	**Average Speed (m s^{-1})**	**Average safe draft (kN)**		**Power Output (kN)**	
		27ºC	**34ºC**	**27ºC**	**34ºC**
500	0.8	0.50	0.40	0.43	0.35
600	0.8	0.60	0.50	0.52	0.43
700	1	0.67	0.57	0.68	0.58
800	1	0.75	0.65	0.77	0.67
900	1	0.83	0.72	0.85	0.73
1000	1	0.90	0.80	0.92	0.77

Power accessibility at farm level is a significant factor constraining crop production in the semi-arid tropics. Giles (1975) approximated available agricultural power in percentage by geographical region and source as presented in Table 2.2. He proposed that at least 0.37 kW per hectare is required for significant returns.

Table 2-2 Agricultural Power by source and geographical region (Giles, 1975).

Region	**Total (kW/ha)**	**% of available power /ha**		
		Man	**Animal**	**Engine**
Asia	0.16	26	51	23
Africa	0.08	35	7	58
Latin America	0.19	9	20	71
Total %		24	26	50

2.2.2 Agricultural Mechanization in Kenya

The European settlers introduced draught animal technology in Kenya in 1910. Smallholder farmers in Ukambani were the first to adopt the technology. By the year 1930, the technology had spread widely in the region. According to Bymolt and Zaal (2015), Sub Saharan Africa (SSA) has the lowest uptake of mechanization globally and is highly dependent on manual labour. For instance, Nationally Kenya has a 30% use of motorized power, 50% hand and 20% animal draught (FAO, 2006; MoAL&F, 2017).

Kenya Revenue Authority (KRA) records reveal that the sale of 4-wheel tractor has risen slowly from 6422 units in 1961 to 12844 units in 2002 (Mutua, 2014). However, most of these tractors are owned by large commercial farms. Among small-scale farmers, tractor ownership stands at 5% and is highly dependent on human and animal power (Bymolt and Zaal, 2015).

2.2.3 Draught Animal Power

In Kenya, the European settlers introduced the use of oxen for cultivation in the 1920s from South Africa (Oudman, 1993). Oxen and donkeys are the main draft animals used in Kenya and to a limited extent, camels. Use of draft animal in farm operations has been spreading slowly in Africa as compared to other continents (Starkey, (1994). In Kenya, use of animal traction is relatively low. It is estimated that only 12% of smallholder farms (with total land size of less than 10ha) use animal traction, 3% use tractors and over 80% use hand tools (Mutahi, 1993).

At the point of adoption of animal traction, the animals were generally used for primary tillage. Mechanization of subsequent farm operations, for example, weeding may not pursue for many years since farmers are reluctant to allow animals into fields with crops. However, over time animal-powered weeding is becoming more common in most African Countries. In nations with extensive experience of animal power, including Senegal, Zimbabwe, Southern Mali and South Africa, most of the farmers using animals now weed with animal power. In other different regions, including some part of Malawi, Tanzania and Zambia, just a minority (yet an increasing population) use weeders. While the introduction of weeding innovations has been associated with specific agricultural extension pragramme, in a few areas weeding seems to have developed by farmers' innovations. For instance, in the Machakos region of Kenya, farmers use their ploughs for weeding (Tiffen *et al*, 1994).

In 1903, European farmers and traders began to settle in the Machakos District of Kenya. They used heavy ploughs that required groups of six animals. There was no formal advancement of animal traction, yet ploughs were accessible from traders. Some local Kamba farmers begun utilizing ox-ploughs in 1910. By 1912, the District Commissioner had noticed an expansion in farm size and cash crop production because of the innovation. By 1933, there were an approximated 600 ploughs in use. The lighter Ransome Victory plough bacame accessible during the 1940s, and turned into the most well-known implement. By the late 1950s, practically all farmers in the District (presently Machakos and Makueni Counties) were utilizing animal power, through ownership or contractual. This high rate of adoption because of the private sector sourcing of the implements and without any stimulation from formal extension or or credit programs (Tiffen *et al*, 1994).

2.2.3.1 Draught capability of work animals

According to Inns, (1996), the draught ability of an animal is the power that it can exert to draw an implement. Animal's draught ability is limited by physiological, biomechanical and environmental factors. These are dependent on:

(i) Characteristic of the particular animal e.g. the species, health, nutrition status etc.
(ii) Operator's skills to use and manage the animals.

As indicated by Harrigan and Roosenberg (2002), well-managed bulls are equipped for working draft load estimated as tension (kg-power, kN) equivalent to 10-12% of their body weight while working throughout the day and more enhanced loads for brief periods of time. Generally, bovines (mainly cattle and buffaloes) should have the ability to provide a sustainable draught force equivalent to 10-12 % of their body weight. On the other hand, equines (donkeys, horses and mules) as well as camel have the ability to sustain draughts of between 12 and 14 % of their body weight (Inns, 1996).

Table 2-3 Draft capability and power output of various animals

Animal	Average weight (kg)	Approximately draft capability (N)	Average speed (m/s)	Power developed (W)
Ox	500-900	600-800	0.56-0.83	560
Cow	400-600	500-600	0.70	340
Water buffalo	400-900	500-800	0.80-0.90	560
Horse	400-700	600-800	1.0	750
Mule	350-500	500-600	0.9-1.0	520
Donkey	150-300	300-400	0.70	260
Camel	450-500	400-500	1.1	500
Man	60-90	300	0.28	75

Source: from Campbell, 1990

2.2.3.2 Principal types of cultivation implements

Two fundamental animal draught implements are beam and chain pulled. Beam pulled implements trace their origin more less directly from the initial animal draught implement that was in use more than 4000 year ago as recorded by Inns (1996). Since then, improvement has prompted numerous designs that are incredibly efficient and easy to operate. Beam- pulled implements are the commonly used throughout Asia and it neighboring regions (Gebregziabher *et al.* 2006).

Plate 2-1: Two-ox shoulder yoke

In Latin America, Africa and south of the Sahara, the chain-pilled implements are extensively used having been ushered in from North America and Europe. Early European ploughs used different devices to support part of their huge weight. Some relied on wheels, while others, such as swing plough, were fitted with a soleplate or slade, which offered support by sliding on the furrow bottom ((Gebregziabher *et al.* 2006).

Majority of the swing ploughs made in India and Africa are based on 1930s designs. They weigh roughly 35 to 40 kg - and are fitted with a little nose wheel towards the front of the bar to help with turning and transport. The nose wheel is not supposed to help the plough in work, endeavors to utilize it for that purpose have prompted excessive wear on bearing, difficulties of control and adjustments and inefficiency in field operations. (Inns, 1996).

However, using higher grade of still, modern swing ploughs can be made lighter, stronger and more affordable. The improved designs weight less than 18kg and therefore the do not require a nose wheel. With proper design and use with suitable harness, improved swing ploughs are easy to manage during farm operations (Brunt, 2003).

2.2.3.3 The role of draft animals

From statistics, it is demonstrated that human power is still prevails over a significant part of the developing countries, accounting for over 70% of agricultural power demand. (Twomlow *et al.*, 2002). Approximately a quarter of the agricultural power required is derived from draft animals while tractor power accounts for only 6% (Table 2-4).

Table 2-4 Proportional contribution to total power use in selected regions-(%)

Region	**Human**	**Animal**	**Tractor**
N Africa	16	17	14
Sub-Saharan Africa (SSA)	89	10	1
Asia (excluding China)	68	28	4
Latin America	59	19	22
Overall	**71**	**23**	**6**

According to Ellis-Jones, J *et al*, (2004), in Sub-Saharan Africa, most rural population rely on human or animal power for their farm operations. Human powered farm operations are hard, backbreaking and gives extremely low returns. It has therefore remained unpopular and a main reason why younger people are not interested in agriculture.

2.3 Effect of Tillage on Soil Parameters

Tillage is directly or indirectly affected by soil parameters such as soil temperatue, moisture content, bulk density, porosity, structure and penetration resistance (Bronick *et al.*, 2005)

Guan, *et al.* (2014) reported that different tillage practices affect soil porosity, bulk density, field capacity, particle density as well as the permanent wilting point. They observed that after four years, soil bulk density decreased depending on tillage methods used. Highest decrease was reported for zero tillage while deep tillage reported the lowest reduction. A similar scenario was reported for soil particle density and the permanent wilting point. Porosity, field capacity was reported to increase due to different tillage methods which included; conventional tillage, zero tillage, deep tillage and minimum tillage.

Evolution of soil properties in a no-tillage system is as a result of the intrinsic qualities of soil, soil profile strata and the prevailing climating condition as well as the histrorical soil management practices. Researchers have reported higher bulk density values for conservation tillage in comparison to conventional tillage (Ferreras *et al.*, 2000; Liu *et al.*, 2013) while others have reported that there is no significant difference between the two tillage methods (Rusu,2014) or defined lower values in conservation system with mulching (Lal *et al.*, 1994; Edwards *et al.*, 1992)

Penetration resistance is an indication of the degree of soil compaction or the existence of a hard pan within the soil profile. Research have reported a reduction in root development and poor nutrient and water update by crops owing to increased penetration resistance (Moraru *et al.*, 2010).

Changing infiltration, evaporation and surface runoff as a result of tillage system, has significant effect of soil moisture content. Sarauskis et al. (2009a) reported superior water storage capability under conservation tillage compared to conventional tillage. Enhanced soil water storage under conservation tillage can be credited to reduced evaporation, enhanced infiltration, and soil protection from rainfall impact

2.4 Soil Compaction

According to Lull (1959), Gitau (1995) and Payne (2008), soil compaction is an unwanted condition in agricultural land as it reduces soil infiltration capability leading to an increase in surface runoff and subsequently excessive top soil wash away. Soil compaction affects soil biological, physical and chemical parameters as well as impeding plant root development. Reduced root development affects efficiency in water and nutrients uptake.

Johnson *et al.* (1990) stated that under surface and subsurface crusting the soybean yields remained unaffected while maize production decreased substantially. The observation were in harmony with Tardieu (1988) who reported different response to soil compaction for different crops species and different crop varieties. For instance, cowpeas are able to develop well at a level of soil compaction that inhibits roots development in maize.

Soil compaction caused by conventional farming practices such as tillage, agricultural machinery working in poor soil conditions is the worst form of land degradation according to McGarry (as cited in Benites *et al.,* 2005). Animals trending in farms during grazing also causes compaction. Conservation farming has been reported to improve soil physical paremeters by reducing the mechanical soil disturbance (Losada *et al.,* 2005). However, according to Blanco-Cangui (2008) a shift from convention to conservation farming systems may cause an increased soil compaction due to lack of frequent soil loosening particularly for no-tillage systems with poorly drained clay soils. Thus, the need to rip and subsoil the fields after 2 to 3 years of continued conservation farming.

2.5 Sub-soiling

Godwin (2007) studied the impact of Sub-soiler speed on forces and soil aggravation in compacted loam and clay soils. He reported significant linear effect of tool speed on vertical force and quadratic effects on horizontal forces, specific resistance and moments. Onwualu and Watts (1998) in a study on the correlation between tillage tool speed and forces found the tool force (vertical force and draught) are a function of tool speed and the square of the tool speed.

2.6 Tool Design

McKyes and Maswaure (1997) studied the effect of design parameters of flat tillage tools on loosening of a clay soil and found the draft requirement to increase with width, depth and rake angle of the tillage tool. For a Calcic Chernozem and HaplicKastanozem soils, based on the FAO classification, draft increased less above a critical speed range of 3 to 5 m s^{-1}(Kushwaha and Linke, 1996). The design of conservation tillage tools to accomplish different jobs is a very complex engineering work (Shmulevich, 2007). This is because different crops require different soil preparations (Dardanelli ital., 1997). Different soil conditions also require different tillage operations. Shape and size are usually the first parameters to be considered in the design of any tillage tool (McKyes and Maswaure, 1997). The shape influences the pattern of soil movement and final soil conditions while the size determines the power required to pull the tool through the soil. Although the designer can control tool shape and size, tools cannot perform optimally without proper combination and orientation of the tool design parameters (Stolterman and Pierce, 2012).

Godwin and O'Dogherty (2007) stated that vertical forces and draft can predicted with an average error of -3 and +33% respectively. The majority of the predicted values were within ±20% and ±50% of measured value.

2.7 Draft animal implements

The farm implements help in transforming the power of draft animals into work effort in the farm. Without proper tools, no efficient work can be achieved. The oxen farmer requires different tools for the different farm operations. All working tools like plough, harrow, ridger and cart, etc., are attached to the draft animals by means of the harness (i.e. part of the equipment attached/put on the animal). All other farm implements are attached to the harness. The harness allows us also to control the draft animals. The oxen harness consists of the; halter chain or nasal ring, yoke, head joint rope, steering rope (Fischer, R. 1995).

Halter Chain or Nasal Ring are used to tie the head joint and the steering ropes to the oxen and should be adjusted properly to avoid wounding the animal, there are two systems:

- The Nasal Ring, made of steel and applied by the veterinary staff to the nose of the ox, is very effective. Oxen can be trained faster and are easier to control.
- The Halter Chain, made of a chain and attached to the head of the ox. is less effective. Oxen are more difficult to train and to control with this system (Oudman, L. 2004).

The head joint and steering ropes are attached to the halter chain or nasal ring to control the oxen. The steering rope is 12 mm thick and 20 m long, head joint rope is 6 mm thick and 2 m long. A yoke is used to the two oxen. All traction implements are attached to the yoke by the pulling chain (plough, ridger, and harrow) or the beam (cart, roller cutter).The yoke consists of the yoke beam, the yoke pegs and the peg beam. Yokes are of two type;

- -The short yoke with a length of about 1.3 m, used for plowing, harrowing, transport, clearing.
- The long yoke with a length of about 1.7 m and adjustable to different working distances, used mainly for ridging, weeding and moulding.

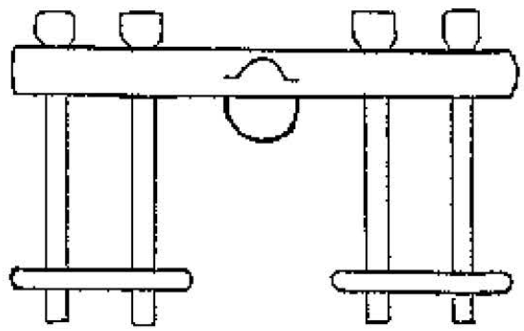

Figure 2-1: Yoke (Source (Fischer, R. 1995).

The pulling chain is used in connects the implements with the harness. It is 2.5 m long and can be adjusted to different lengths

2.8 Specific Draft Requirement

Specific draft requirements is an important parameter in measuring and evaluating the performance of tillage equipment. Therefore, specific draft is considered as essential data when attempting to correctly match tillage equipment to a prime-mover (Sahu and Raheman, 2008). Al-Suhaibani (2010) conducted studies to determine draft and power requirements of tillage equipment under different soil conditions. Equipment width, operating depth and speed were factors found to affect draft requirement of a tillage equipment.

Draft is also a function of tillage tool geometry (Tong and Moayad, 2006). The effect of speed on equipment draft requirement depends on the soil type and the type of equipment (Al-Suhaibani, 2010). Sub-soiling should be done when the soils are dry and friable. If the soils are too wet, subsoiler shafts will slide through the ground with little penetration without breaking up the hard pan. On the other hand, if the soils are too dry, it will be difficult for the subsoiler to get into the ground therefore requiring a more powerful prime mover to penetrate the subsoiler through compacted soil layer. Soils, particularly those with higher clay content, can break into huge clods if conditions are excessively dry. For most regions, perfect subsoiling conditions are before the soils are excessively dry. Soils ought to disintegrate without staying together, yet not be so dry and hard that they cannot be broken up effectively.

The draft requirement for ploughing are summarized in Figure 2-1. The amount of pull that has to be provided can be roughly predicted from the soil type and quantity (as represented by its "specific resistance"-one of the soil's physical parameters) and the design and setting of the plough.

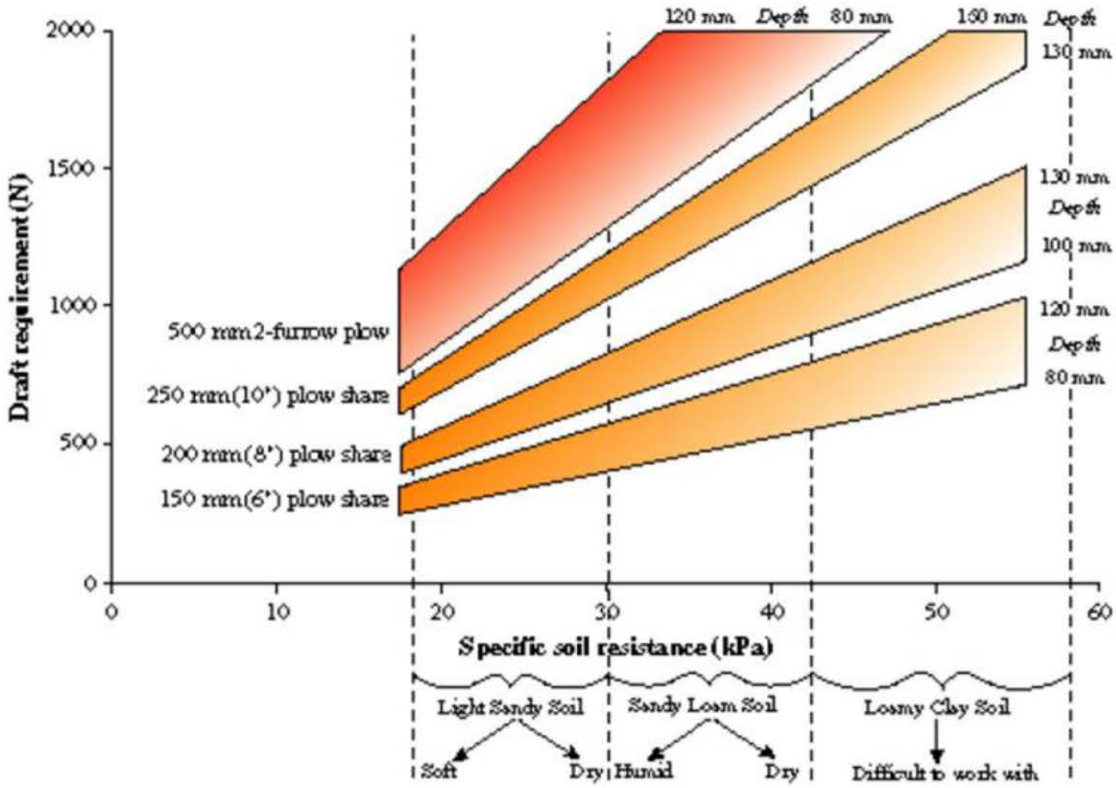

Figure 2-2 Draft requirement for ploughing in relation to soil type and width of cut (Sims *et al.* 2002)

2.9 Summary of the Literature Review

Soil shear strength and draft force requirements of a tillage tool are functions of soil deformation rate. It follows therefore that during the execution of the field tests, operating speed should be kept close to constant so that a uniform speed influence on the collected data is maintained. Soil water content has been reported to be an influential factor of the soil characteristics and draft force requirements of the tillage tools thus influencing the size of the soil cross-section area tilled. At the same time, it affects the soil-failure type. It was therefore important to determine the variation in soil water content during the field tests for the different test plots. The rake angle, geometry of the tool and operating speed have been proven to influence both the soil-failure types and rupture planes.

To have the same type of soil-failure and rupture planes, the rake angles and the geometry of the blades for sub-soilers should be maintained for each test. The reviewed literature has shown that the draft force requirements of a tillage tool increased when operated below its critical depth. It was therefore hypothesized that when the sub-soiler is operated above the critical depth, energy utilization would be optimized. During the field test, different depths will be used in optimizing the depth of sub-soiling as the hitching length also varies.

CHAPTER THREE: THEORETICAL FRAMEWORK

3.1 Preamble

In this chapter, the principles and theories used in achieving the objectives of the study are described the models and mathematical equations developed by others research in relation to this topic of study are outlined and the terms in the equations or models explained.

3.2 Draft Power

Kruger *et al*. (1982) stated that the drawbar energy required to till a given area is dependent on tillage depth and implement travel speed. Upadhyaya *et al*. (1995) published the following equation for draft requirement of a subsoiler:

$$D = B_o(CI \times W)d + B_1(\rho_w)d \times W \times S^2 \quad (3.1)$$

Where

D	= Draft (F)
CI	= Cone Index (FL^{-2})
W	= Width of subsoiler cutting edge (L)
D	= depth of operation (L)
ρ_w	= wet bulk density (ML^{-3})
S	= travel speed (LT^{-1})
Bo, B1	= constants

Draft power is a measure of the work accomplished according to the equation

$$D_p = \frac{F \times D}{T} \quad (3.2)$$

Where:

D_p	= draft power (watts)
F	= force (Newtons)
D	= distance (meters) and
T	=time (seconds)

Draft power is directly proportional to draft force and speed, which reduces the time required to complete a task.

Draft refers to the force necessary in moving an implement in the travel direction. For most implements, soil resistance and crop residue (Hamlett *et al.*, 1990) mainly influence draft required.

Dry and compacted soil has great resistance to the tillage implements than compared to moist and unconsolidated soils. Tractive surface also has a great influence on the draft. Loose soil results in increased tractor wheels' slippage that in turn affect the draft required. In addition, the slope affects draft requirement. For instance, draft is increased when the tractor is moving upslope. Another factor that affect draft is the depth of tillage (Kees, 2008).

3.3 Soil Classification

Soil classification through texture analysis is done using the Buoyocos method. The percentage silt, clay and sand fractions are computed using equations 3.3, 3.4 and 3.5. The percentages obtained and the Soil texture triangle Figure 3-1 are used to classify the soil.

$$\text{Sand} = 100 - 2((H_1 - B_1) + 0.36(T_1 - 20)) \tag{3.3}$$

$$\text{Clay} = 2((H_2 - B_2) + 0.36(T_2 - 20)) \tag{3.4}$$

$$\text{Silt} = 100 - (Sand + Clay) \tag{3.5}$$

Where;

H_1 = hydrometer reading at 40 seconds after stirring

H_2 = hydrometer reading 3 hours after stirring

B_1 = hydrometer reading 40 seconds after stirring for the blank

B_2 = hydrometer reading 3 hours after stirring for the blank

T_1 = Temperature reading 40 seconds after stirring

T_2 = Temperature reading 3 hours after stirring

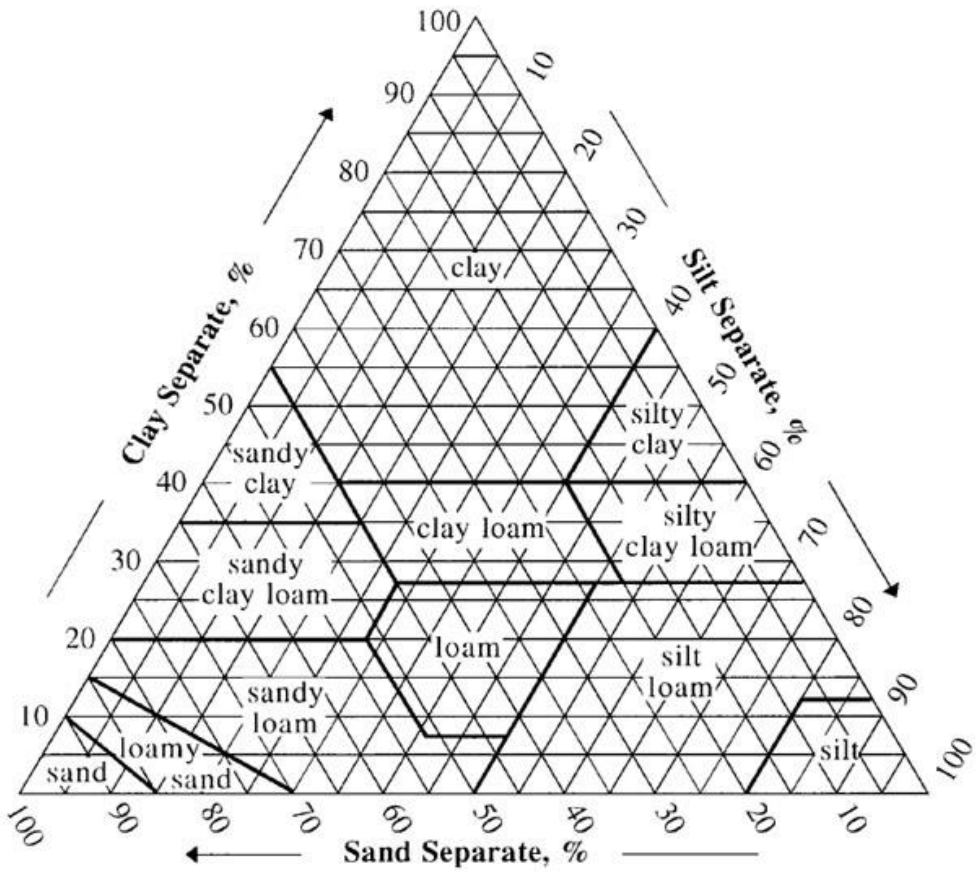

Figure 3-1 Soil texture triangle (Source: USDA-NCRS: http//soils.usda.gov)

3.4 Soil shear Strength

Soil shear strength refers to the maximum shear stress a given soil structure can support without any further compression. This is of agricultural and engineering importance in conserving the soil against compaction by farm machinery and animals. It is also important in informing the design of tillage implements used in alleviation of soil compaction. Soil strength is defined by the extent of cohesion and internal friction existing between soil particles. The strength of the soil has a bearing on root penetration and seedling emergence.

Soil shearing strength is composed of cohesive component and frictional component (McKyes, 1985). Empirically the Mohr – Coulomb equation 3.6 as cited in (McKyes, 1985) and (Davies, 1985) define the soil shear strength

$$\tau = C + \sigma \tan \Phi \qquad (3.6)$$

Where;

Ʈ	= Soil Strength
C	= Soil Cohesion
Σ	= Normal Stress
tan Φ	= Coefficient of friction

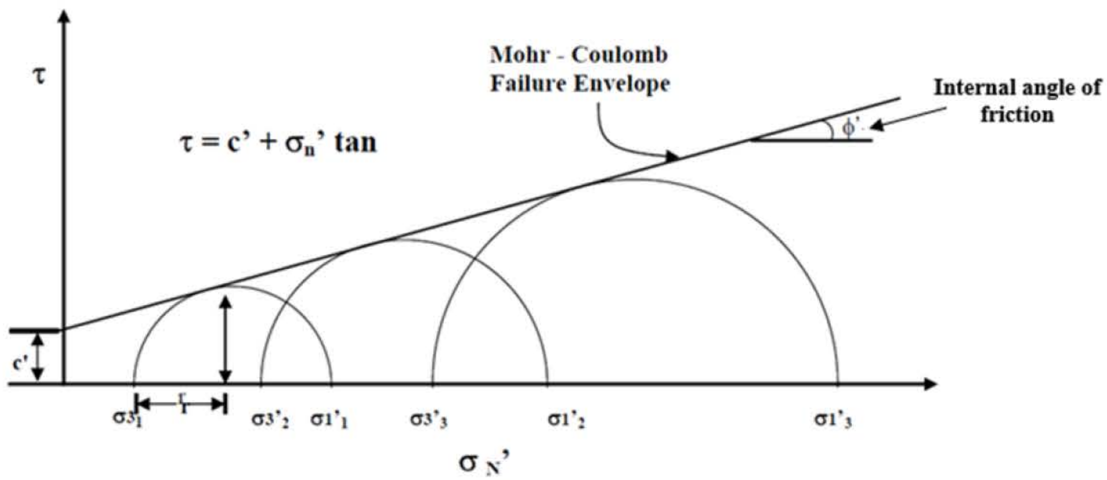

Figure 3-2 Mohr Circles

3.5 Penetration Resistance

The following equation were used in determining soil penetration resistance (in situ testing penetrometers);

$$CR = I \text{ x } \frac{CS}{AC} \qquad (3.7)$$

Where;

CR	= Cone resistance (N/cm^2)
I	= Impression on the scale (cm)
CS	= Spring Constant (N/cm)
AC	= Area of cone (cm^2)

3.6 Soil Moisture content

Refers to the quantity of water in a given volume or mass of soil. Soil moisture (M.C) can be expressed in different form;

i. Gravimetric – Dry-weight Basis

The range is usually from zero to infinity. It is the commonly used method of expressing moisture content.

$$W_d = \frac{\text{grams of water}}{\text{grams of dry soil}} \tag{3.8}$$

ii. Gravimetric – Wet-weight Basis

This ranges from 0 to 1 or from 0% to 100%

$$W_d = \frac{\text{grams of water}}{\text{grams of moist soil}} \tag{3.9a}$$

$$= \frac{\text{grams of water}}{\text{grams of water} + \text{grams of dry soil}} \tag{3.9b}$$

3.7 Bulk Density of soil

The bulk density of soil refers to the ratio of weight of dry soil (Ms) to the total volume of soil V. Total soil volume represent the volume of solids and the volume of voids which may contain air or water or both. Soil bulk density and soil porosity are important indicators of soil suitability for root growth and water permeability and vitally important for the soil-plant system (Rai, *et al.,* 2018). Soils with a high total pore space have a low bulk density and conversely low porosity leads to high bulk density (Cetin *et al.*, 2007).

$$\text{Bulk Density}\left(\frac{\text{g}}{\text{cm}^3}\right) = \frac{\text{Dry soil weight(g)}}{\text{Soil Volume (cm}^3)} = \frac{M}{\pi R^2 L} \tag{3.10}$$

Where:

M = Mass of the dried soil sample,

R = Radius (internal) of cylinder and

L = Length of cylindrical sample corrected for any loss of soil.

CHAPTER FOUR: METHODOLOGY

4.1 Preamble

This chapter includes the description of the study area, research process design and methodology used in achieving the objectives of the study. It also details the sampling and data collection techniques, laboratory testing methodology and data analysis procedure.

4.2 Research Study Area

Two experimental plots were used during the study i.e. one in Machakos County and a second one in Kitui County. The two counties of study were selected because animal draught is extensively used and this makes it easier for adoption of the research findings.

4.2.1 Kitui County

Kitui County covers an approximate area of 30,496 km^2. It borders Machakos and Makueni Counties toward the West, Tana River County toward the East, Taita-Taveta County toward the South and Embu and Tharaka-Nithi Counties toward the North. As per the 2009 National Census, Kitui is home to 1,012,709 individuals (Male - 48% and Female - 52%) and has an average growth rate of 2.1%.

The County is generally dry and hot with temperatures extending between 14°C amid the coldest months (July-August) and 34°C amid the most blazing months (January-March). The area gets between 500 and 1050mm of precipitation every year, with normal precipitation of 900mm a year. It has two rainy seasons; March-May (long rains) and October -December (short rains).

Farming is the foundation of Kitui County's economy. In the highlands, farmers are engaged with subsistence farming – growing: tobacco, cotton, maize, sisal, cassava, mangoes, beans, pigeon peas, sorghum and millet. In the lowlands, farmers rear livestock - mostly goats, sheep, cows and poultry as a way of enhancing their income (Kenya-data control, 2018).

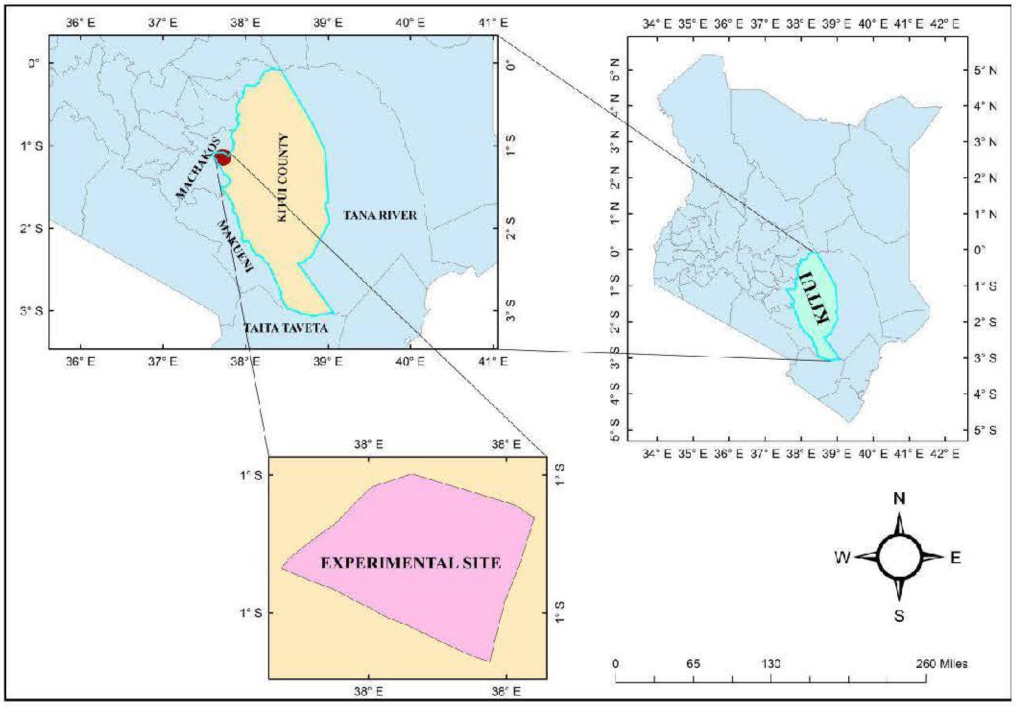

Figure 4-1Map of Kitui County

4.2.2 Machakos County

Machakos County stretches from latitudes 0.75ºS to 1.51ºS and longitudes 36.75°E to 37.75°E. The Fcounty has an altitude of 1000 - 1600 meters above sea level. It has a total Population of 1,098,584 people (Male - 49% and Female - 51%), 264,500 households and covers an area of 6,208 km^2. The local climate is semi-arid with a hilly terrain covering most parts of the county. The area gets between 500mm and 1050mm of precipitation every year, with normal precipitation of 900mm a year. It has two rainy seasons; March-May (long rains) and October – December (short rains).

Subsistence agriculture is practiced with Maize and drought-resistant crops such as sorghum and millet being prominent.

However, the County also plays host to the open air market concept with major market days where large amounts of produce are traded. Fruits, vegetables and other food stuffs like maize and beans are sold in these markets.

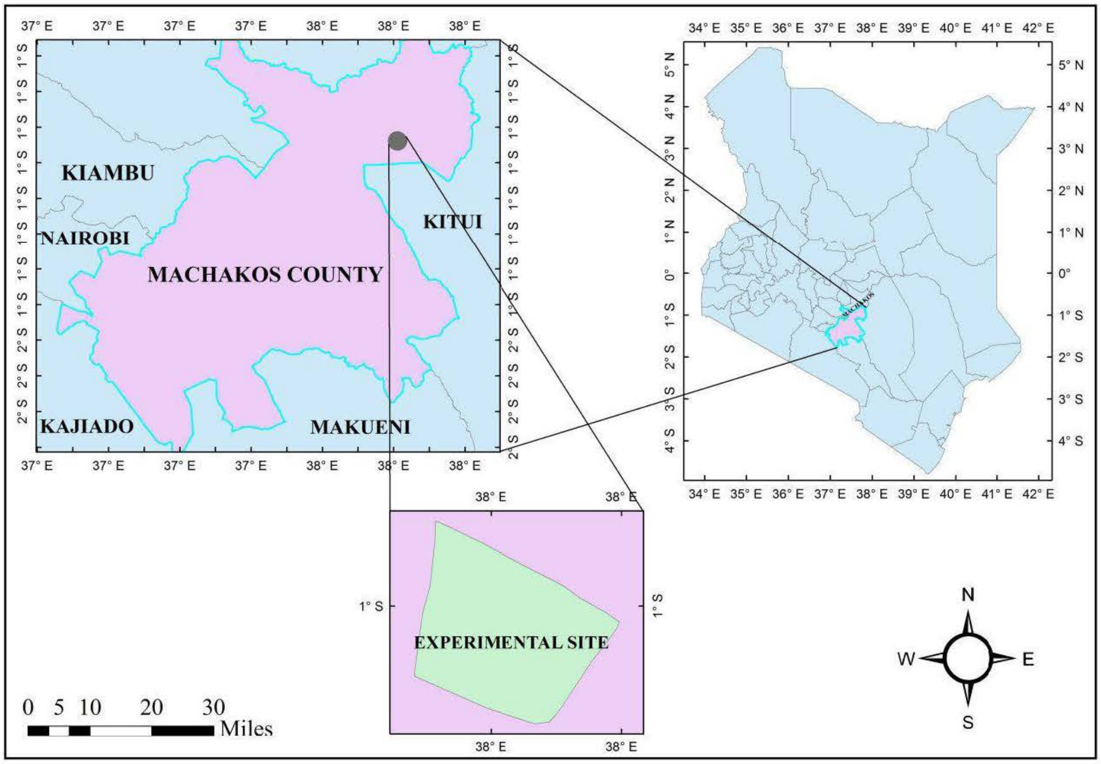

Figure 4-2 Map of Kenya shows Machakos County

The coordinates for the two experimental fields are presented in Table 4-1

Table 4-1 Experimental sites coordinates

Site	Plot Edges	Northing	Easting
Machakos	A	1° 8'34.73"S	37°43'15.77"E
	B	1° 8'33.37"S	37°43'12.74"E
	C	1° 8'31.97"S	37°43'14.61"E
	D	1° 8'32.61"S	37°43'16.41"E
Kitui	A	1° 1'59.43"S	37°40'32.28"E
	B	1° 1'57.71"S	37°40'27.07"E
	C	1° 1'51.79"S	37°40'27.90"E
	D	1° 1'55.66"S	37°40'34.89"E

4.3 Data Collection

4.3.1 Experimental set up and methodology

Field and laboratory experiments were conducted to determine numerical factors of soil shear strength, soil moisture, penetration resistance and soil bulk density. Draft requirement was measured using the MSI 7300 digital dynamometer attached between the equipment and the bullocks as shown in Figure 4-3 using hitches and steel shackles. The dynamometer remotely was communicating with a data logger MSI 8000 RF connected to the computer capturing the draft power instantaneously.

Figure 4-3 the experimental set-up

Plate 4-1 Equipment arrangement for draft data collection

The sub-soiler was attached to the frame as shown in Figure 4-4 and Plate 4-2.

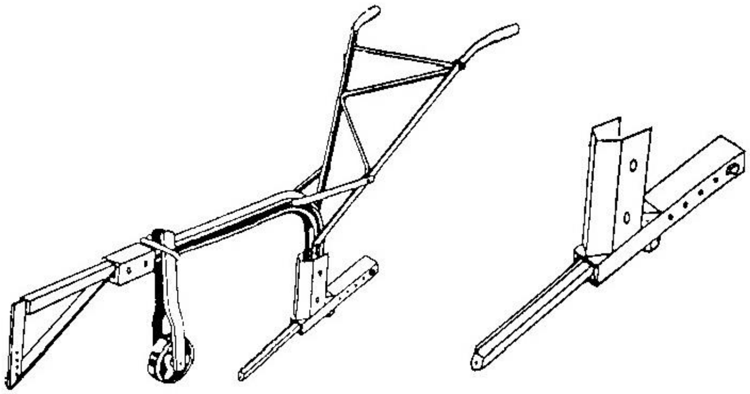

Figure 4-4 Subsoiler Attachment (Starkey etal., 1999).

Plate 4-2 Subsoiler Attachment

At the start of the experiments, a run of the system described in Figure 4-3 was done with the tillage tine disengaged to establish the rolling resistance of the towed equipment. Draft for each hitch length and depth of sub-soiling combination was determined by subtracting rolling resistance from the draft obtained when the tool is engaged.

4.3.2 Experimental Design

The parameters which were investigated for the draft measurement included width; and depth of tillage. For a specified speed, three hitch lengths (L_1, L_2 and L_3) and three depths (D_1, D_2 and D_3) were used in combination. Depth was measured as the vertical distance from the top of the undisturbed soil surface to the equipment deepest penetration depth. This was varied from 0 to 30cm with intervals of 10cm being maintained. For each set up, three replications were performed giving a total of 27 treatments.

The experiments were conducted in Kitui and Machakos Counties with one-test sites in each County. Nine (9) experimental plot of 30 meters by 5 meters each were used. Randomization was carried out for each hitch length and sub-soiling depth for the three replications.

The selection of the two Counties for experimental work was informed on the premise that the use of animal traction has a long history in the two Counties where farmers even use the animals draft in ploughing, crop planting and weeding. Comparison in two independent sites was paramount to enrich this research work based on the results. Further the two Counties borders one another and therefore there was considerable saving in cost and time.

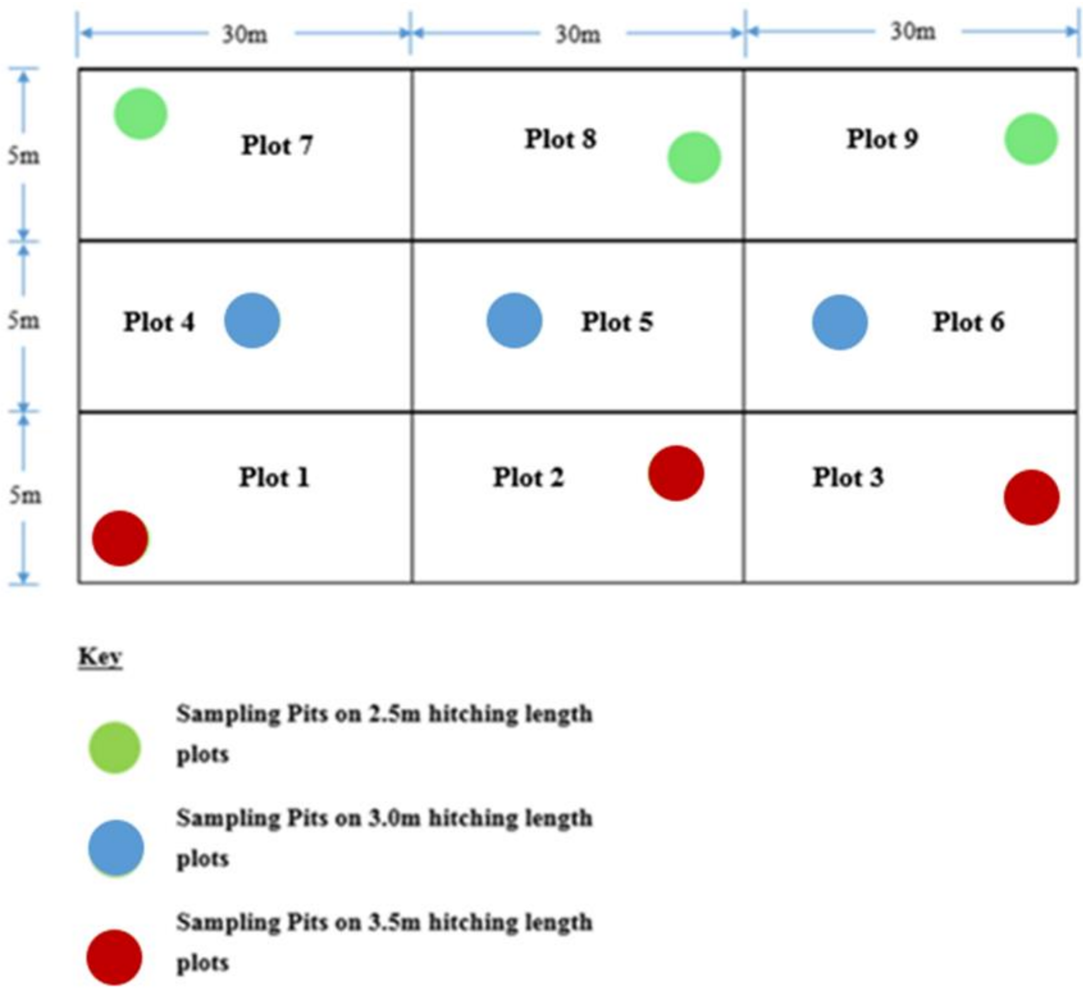

Figure 4-5 Experimental Fields lay-out

4.3.3 Specific Draft

To determine the draft requirement, the arrangement in Figures 4-3 and 4 -4 and in plates 4-1 and 4-2 was used. MSI-7300 dynamometer reading were transmitted remotely to a computer through MSI-8000 RF data logger. To determine the actual draft requirement for each tillage depth at varying hitching lengths, the rolling resistance was subtracted from dynamometer reading when the sub-soiler was engaged. Outliers in the draft data collected were eliminated using the interquartile range analysis.

This was achieved by computing the First Quartile (Q_1), Third Quartile (Q_3), the Interquartile range(Q_r), the upper bound (U_b) and the Lower Bound (L_b) of the data.

The First Quartile (Q_1) was determined by calculating the median of the lower half of the data after getting the median of the sample data arranged in ascending order. The Third quartile (Q_3) was determined by calculating the median of the upper half of the data. The interquartile range (Qr) was then obtained by subtracting (Q_3-Q_1).

The Upper Bound (U_b) and Lower Bound (L_b) were computed using equations 4.1 and 4.2 respectively:

$$U_b = Q_3 + (1.5xQ_r) \tag{4.1}$$

$$L_b = Q_1 - (1.5xQ_r) \tag{4.2}$$

To compute the specific draft (kN/cm^2), equation 4.3 was used.

$$\text{Specific Draft}\left(\frac{\text{kN}}{\text{cm}^2}\right) = \frac{\text{Dynamometer reading} - \text{Rolling resistance}}{\text{Cross} - \text{sectional Area}} \tag{4.3}$$

The cross-sectional area was obtained as a product of the furrow width and furrow depth measure after the tillage tine has passed.

4.3.4 Soil characterization

The soil physical and mechanical properties (soil moisture, texture, structure, bulk density, shear stress and penetration resistance) were determined during the study. Soil samples were collected randomly to depths of 30cm with each test plot having at least three soil samples. The soil samples were collected using sealed plastic containers clearly labelled with reference numbers indicating the plot and depth from which the sample was collected.

4.3.4.1 Soil Classification

Soil classification was done using the texture analysis method, Soil texture was determined using the Buoyocos method. Samples collected from the field were subjected to texture analysis procedure (Appendix F) and using equations 3.3, 3.4 and 3.5 the percentage sand, clay and silt composition were computed. Using the soil texture triangle Figure 3.1 and the percentages of sand, silt and clay computed, the soil samples were classified.

Plate 4-3 Texture Analysis

4.3.4.2 Soil Moisture Content

Soil moisture content was determined using gravimetric method. The soil samples collected from the experimental sites were stored in seal contains and transported to the laboratory. The samples weights were recorded and the oven dried for 72 hours at temperature of 105^{o}C. The dried samples were then weighted and the moisture content computed using Equation 3.9.

4.3.4.3 Shear Strength

Soil shear strength was determined using the BS 1377-8 procedure. Soil samples were placed in a tray, all the uneven particles removed before pre-moisting to allow remolding. The resulting mixture was moulded by putting a small quantity of the soil into the mould then the soil compacted with a rod until the specimen mould was full. Excess soil was then removed using a scalpel and the mould removed by sliding it outwards on both sides that hold the specimen together.

Plate 4-4 Soil sample remolding for triaxial testing

Plate 4-5 Soil sample on the triaxial machine

The moulded soil sample was shaped to a height of 76mm and placed on the base of the triaxial chamber. It was then placed in a rubber membrane and between porous stones. The remolded sample was then placed in the pressure chamber for axial loading. The chamber pressure was readjusted to the desired chamber level and the pressure valve opened. The pressures used in this study ranged between 100 to 300 kPa intervals. With application of chamber pressure an axial load was applied to produce an axial strain at a given rate of 0.5mm/min at this point, the stop watch will be started.

The data sheet was filled with data of, initial height and weight, final height and weight after deformation, diameter of the sample, the proving ring readings, and time taken to apply an axial load. This procedure proceeded until the sample failed indicated by a decline in proving ring reading.

This procedure was repeated for all the soil samples of the same soil constituent at different chamber pressures.

Mohr circles were then drawn for each data set and the value of internal angle of friction Φ) and Cohesion(C) determined (see Figure 3–2). The internal angle of friction is a measure of the angle between the Normal force and the Resultant force (R) that is attained when failure just occurs in the soil in repose to shearing stress by the implement. Cohesion (C) is the force that must be applied to allow the implement to shear the soil and begin to slide. These two parameter are key in establishing the shear strength required in different soil conditions for various types of tillage implements to shear the soil or make the implement slide. The values of shear strength were computed using Equation 3.3.

4.3.4.4 Bulk Density

This test was carried out to determine the level soil compaction, which has a greater significance in determining the root development and growth. Soils with bulk densities of higher than 1.6 g/cm3 tend to restrict root growth. Undisturbed soil samples collected using rings were weighed and the weight recorded. The samples were placed in an oven for drying. The weight of the dry samples was then recorded and the weight of the core ring without the soil sample determined. After this the moisture content of the soil was computed. The height and diameter of each core ring was measured and recorded and the respective volume computed. This was repeated for all the samples and their respective bulk densities calculated.

4.3.4.5 Angle of Repose/Internal Angle of Friction

Angle of repose was determined using the BS 1377-8 procedure. Triaxial test was carried out to determine the major and minor principal stresses from which Mohr circles were developed and internal angle of friction determined from the Mohr circles (see Figure 3-2).

4.3.4.6 Penetration Resistance

A soil penetrometer with a cone angle of 30^{o} and cone diameter of 12.83mm was used in determining the in-situ soil penetration resistance. The penetrometer was pushed into the soil to a pre-determined depth and penetrometer resistance recorded. The procedure was replicated several times and the average of the values determined as the mean penetration resistance.

Plate 4-6 Penetration resistance measurement

4.3 Statistical Analysis.

The results of the various trials were used to establish, approve and disapprove the hypothesis of this study as envisaged in part 1.6 of this report.

The soil-resistance datasets obtained from the field tests were compared using statistical measures of fit particularly the coefficient of determination (R^2) and the student t-test. The

Coefficient of determination, R^2 is calculated using equation 4.3.

$$R^2 = \frac{SSR}{SST} = \frac{sum\ of\ squres\ explained\ by\ regression}{Total\ sum\ of\ squares} \tag{4.3}$$

Where

$$SSR = \sum (\hat{y} - \bar{y})^2$$

$$SST = \sum (y - \bar{y})^2$$

The value of R^2 ranges between 0 and 1 that is $0 \leq R^2 \leq 1$. If $R^2 = 0$, then the value of y does not depend on x. When $R^2 = 1$ the linear relationship between x and y is perfect that is, 100% of the variation in y is explained by variation in x.

Effects of hitching length on draft power as well as effect of depth on draft requirement were assessed by ANOVA using the linear mixed model in Genstat (Chartier and Cousineau, 2011).

The protected SED mean separation procedure at $P \leq 0.05$ was used to compare treatment means (Saville, 2003). Recorded draft was divided with the sub-soiler's effective surface area, which penetrated into the ground for that given operation to obtain specific draft.

Conclusions on the effect of changing hitch length and sub-soiling depth were made accordingly. Optimum values for the hitch length and depth were obtained and documented for different sites.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Preamble

The chapter outlines the findings and interpretation of datasets obtained during the study. Soil classification and characterization is presented herein, the draft data from the experimental fields at different tillage depths and hitching lengths are provided. Statistical analysis and comparison of draft requirement with changing tillage depth and hitch length are presented in this section. The detailed datasets collected are provided in Appendices.

5.2 Soil Parameters Pertinent to sub-soiling

From literature review, the parameters in Tables 5-1 were found to influence draft requirement for sub-soiling tillage implements.

Table 5-1 Pertinent soil parameters

Soil Property	**Author of study**
Moisture content	Daraghmeh et al. (2009) Makudiuh et al. (2016), Muchiri, G. (2012)
Cohesion and angle of internal friction	Mohsenimanesh *et al.* (2009) Sahu (2008), Ijioma (1995), Tong, J., & Moayad, B. Z. (2006). Gitau *et al.*, (2006) Mwangi *et al.* (2018)
Bulk Density	Tong, J., & Moayad, B. Z. (2006), Sahu (2006), Ndisya *et al.* (2016), Ndisya *et al.* (2016)
Speed of ploughing	Sahu (2006), Mohsenimanesh *et al.* (2009), Ajav *et al.* (2012), Ucgul *et al.* (2017), Ndisya *et al.* (2016)
Depth of ploughing	Ajav *et al.* (2012), Makudiuh *et al.* (2016), Gitau *et al.* (2006) Mwangi *et al.* (2018), Muchiri, G. (2012)
Angle of repose	Shmulevich *et al.* (2007), Ajav *et al.* (2012), Hiuhu *et al.* (2015)
Width of cut	Godwin(2007), Hiuhu *et al.* (2015)
Penetration Resistance	Dexter, A. R *et al.* (2007), Herrick, J. E. *et al.* (2002), Mwangi *et al.* (2018), Muchiri, G. (2012)

5.3 Soil Classification

The soil was classified using the buoyancy method and the results are shown in Tables 5-2 and 5-3 for Machakos and Kitui Sites respectively. The percentage Silt, Sand and Clay were used to classify soil using the texture analysis triangle (See Figure 3-1).

Table 5-2 Soil Texture Analysis for Machakos Site

Sample No:	Depth (cm)	%Sand	%clay	%Silt	Soil Class
	0-10	68	26	6	Sandy clay loam
	10-20	78	20	2	Sandy loam/Sandy clay loam
	20-30	77	20	3	Sandy loam
	0-10	74	22	4	Sandy clay loam
	10-20.	66	30	4	Sandy clay loam
	20-30	65	32	3	Sandy clay loam
	0-10	60	35	5	Sandy clay/Sandy clay loam
	10-20.	56	42	2	Sandy clay
	20-30	50	43	7	Sandy clay

Table 5-3 Soil Texture Analysis for Kitui Site

Sample No.	Depth	%Sand	%clay	%Silt	Soil Class
	0-10	61	26	12	Sandy clay loam
	10-20.	61	28	10	Sandy clay loam
	20-30	55	32	12	Sandy clay loam
	0-10	63	16	20	Sandy loam
	10-20.	67	26	6	Sandy clay loam
	20-30	65	28	6	Sandy clay loam
	0-10	67	22	10	Sandy clay loam
	10-20.	63	29	7	Sandy clay loam
	20-30	59	33	7	Sandy clay loam

Using the texture triangle, it was possible to conclusively determine that the soil is of sandy clay loam type for both Kitui and Machakos sites. However, there were pockets of Sandy clay soil in both experimental sites.

5.4 Shear Strength

Soil shear strength, Cohesion and angle of internal friction obtained from in-situ test are presented in Table5-4

Table 5-4 Soil shear strength for the experimental sites

County	**Depth (cm)**	**Cohesion, C (kPa)**	**Internal Angle of Friction (φ)**	**Shear Strength; τ (kPa)**
Machakos	**0-10.**	5.36	23.06	21.71
	10-20	7.69	27.00	29.60
	20-30	6.30	27.39	28.07
Kitui	**0-10**	7.35	27.39	30.02
	10-20	6.43	29.28	32.86
	20-30	8.43	31.72	39.29

There is a general increase in soil shear strength with increase in depth. At Experimental site in Machakos, the shear strength increases from 21.71 to 29.6kPa from depth of 0-20cm and then decreases to 28.07kPa between 20-30cm indicating the presence of a hard pan between depth of 10-20cm and the soil starts to loosen below 20cm.

In Kitui experimental site, the shear strength increased from a low of 30.02kPa at depths of 0-10cm to a high of 39.29kPa at depths of 20-30cm Figure 5-1. This was indicative of less compacted soils at the surface and presence of hardpan as the depth increases.

For disturbed/remolded samples, the value of cohesion and internal angle of friction were obtained from Mohr circle and averaged 8.7kPa and 22^{o} respectively for Machakos experimental Site. For Kitui site, cohesion and internal angle of friction averaged at 6.57kPa and 29.67^{o} respectively. Samples of the Mohr circles are presented in Figure 5-2 and Figure 5-3 and the rest in appendix B3.

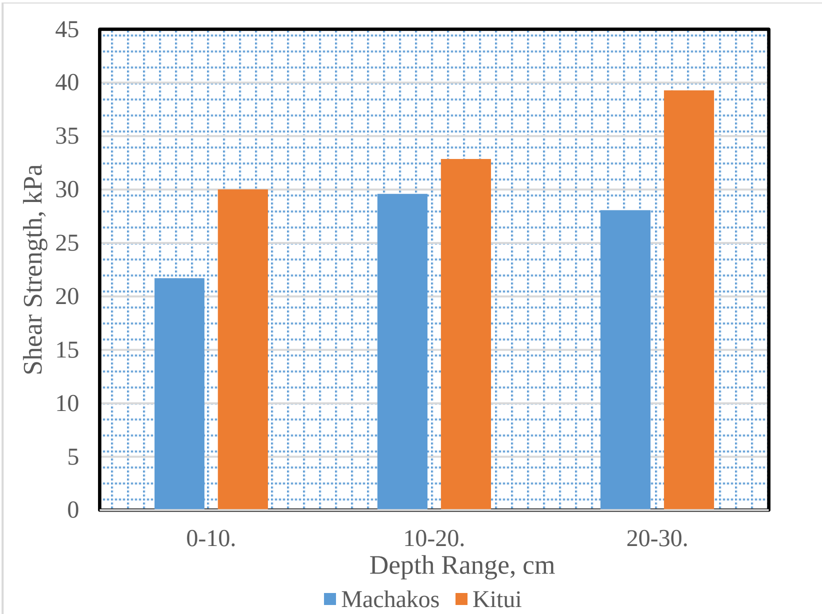

Figure 5-1 Soil Shear Strength for Experimental Sites

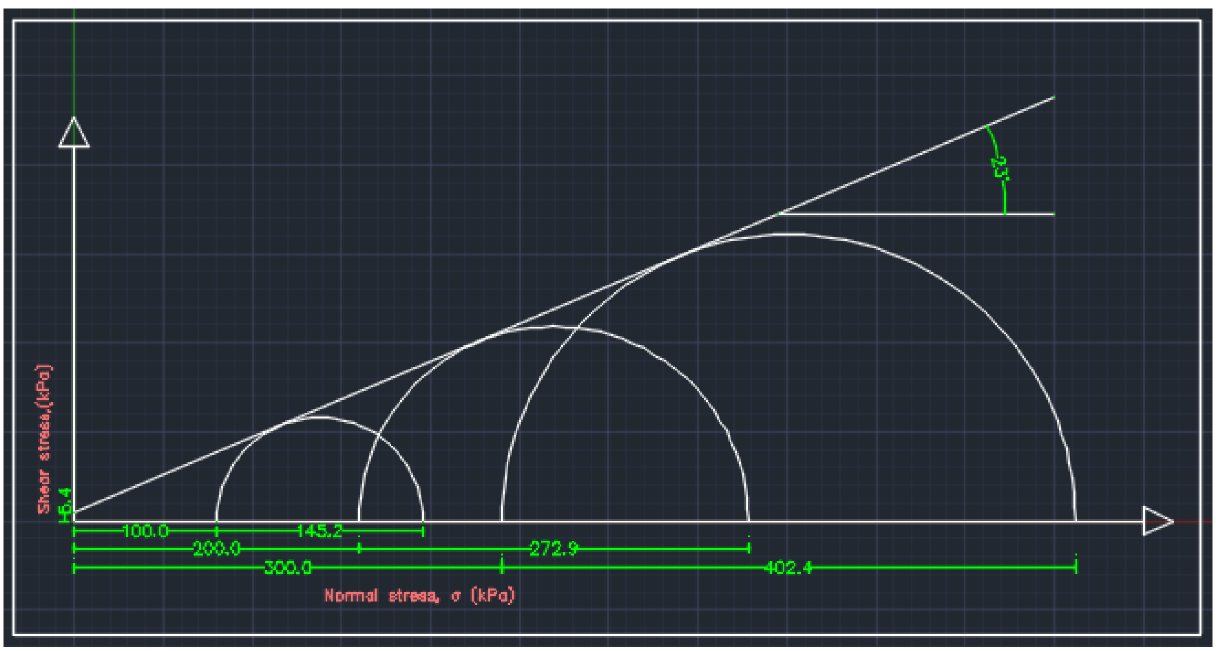

Figure 5-2 Mohr Circle for Machakos Experimental Site

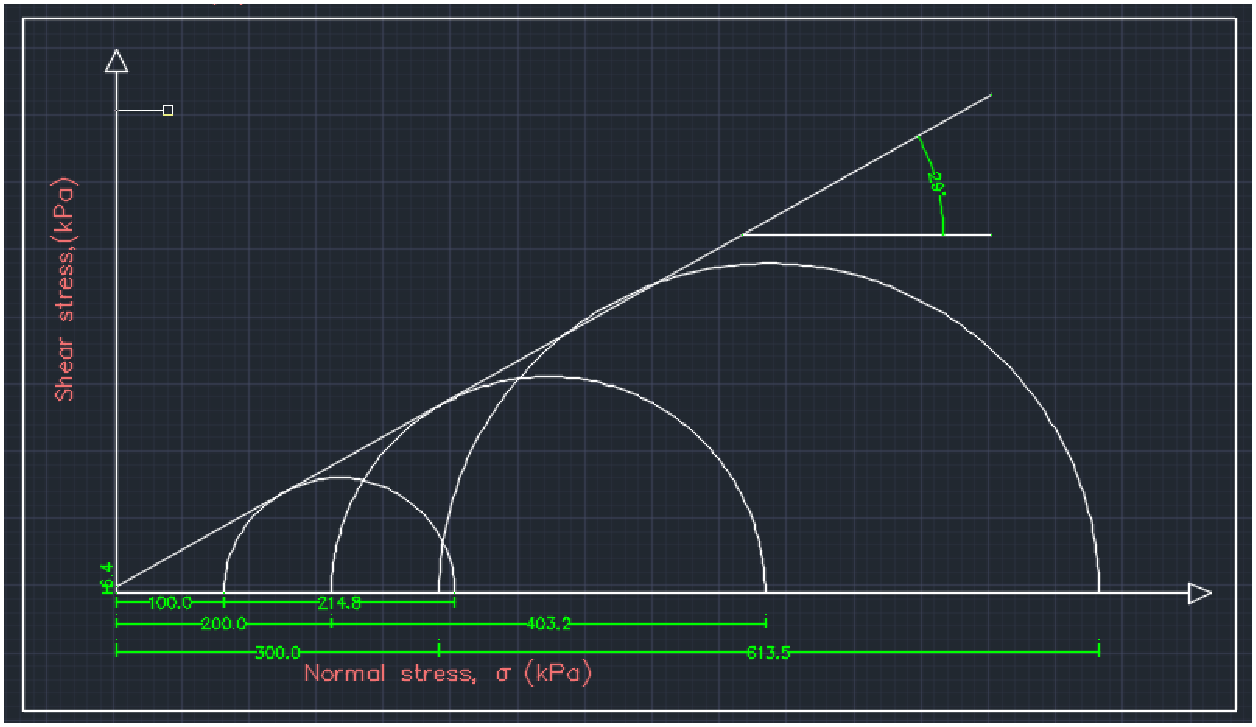

Figure 5-3Mohr Circle for Kitui Experimental Site

Mwangi *et al.* (2018) reported an increase in soil shear strength with increase in depth between depths of 0-45 cm. Wagner, (2013) found out that undrained shear strength increases more or less linearly with depth and shows significantly higher values for an over-consolidated as for a normally consolidated clay.

5.5 Bulk density

Bulk density was computed as a ratio of oven dry weight of bulk sample to the total volume of the soil core ring. For the two experimental sites bulk density values were determined for each range of 10cm depth from 0-30cm and the results are shown in Table 5.5.

Table 5-5 Bulk Density Results for the Experimental sites

Bulk Desnity (g/cm³)						
	Machakos			**Kitui**		
Depth(cm)	**0-10**	**10-20.**	**20-30**	**0-10**	**10-20**	20-30
1	1.53	1.53	1.48	1.30	1.53	1.59
2	1.57	1.45	1.40	1.38	1.62	1.86
3	1.48	1.52	1.46	1.45	1.71	1.87
4	1.58	1.32	1.25	1.40	1.50	1.48
5	1.49	1.49	1.46	1.54	1.51	1.81
6	1.51	1.46	1.27	1.41	1.63	1.82
7	1.53	1.52	1.33	1.61	1.48	1.58
8	1.56	1.42	1.40	1.42	1.49	1.50
9	1.44	1.30	1.28	1.47	1.41	1.55
Average	**1.52**	**1.45**	**1.37**	**1.44**	**1.54**	**1.67**

The average bulk densities for experimental Plot in Machakos decreased with increase in depth from a value of 1.52 to 1.37g/cm3. However, the values for bulk densities for the experimental Plot in Kitui increased with increasing depth from a value of 1.44 to a value of 1.67g/cm3. The results are an indication of soil compaction/crusting on the surface for Machakos experimental field; however, these values of bulk densities are below 1.6g/cm3 beyond which there can be inhibited root growth in soil. In Kitui experimental site the compaction is below the soil surface as indicated by increasing bulk density up to 1.67 g/cm3 at the depth range of 20-30cm.which still is within the range of 1.6g/cm3 beyond which there could be restricted root growth. Twum et al. (2015) reported that soil bulk density is significantly influenced by soil compaction. They also indicated that the bulk density of compacted soils tended to decrease with increasing depth. The dry bulk density for Machakos experimental site is within the normal range of bulk densities for clay soils which is 1.0 to 1.6 g/cm3 (Chaudhari et al., 2013). However, the for Kitui experimental site the bulk density of depth of 20-30cm is 1.67 which is beyond the normal range. The values for the dry bulk densities for the Machakos experimental site can therefore effectively allow plant root development. For Kitui, at depths below 20 cm, bulk density would inhibit root development and therefore ripping is recommended. The discrepancy in the data obtained for Kitui experimental site was as a result of prevailing soil conditions (pertinent soil properties and degree of soil compaction) were different from that of Machakos experimental site and therefore this could have resulted in the identifiable discrepancies.

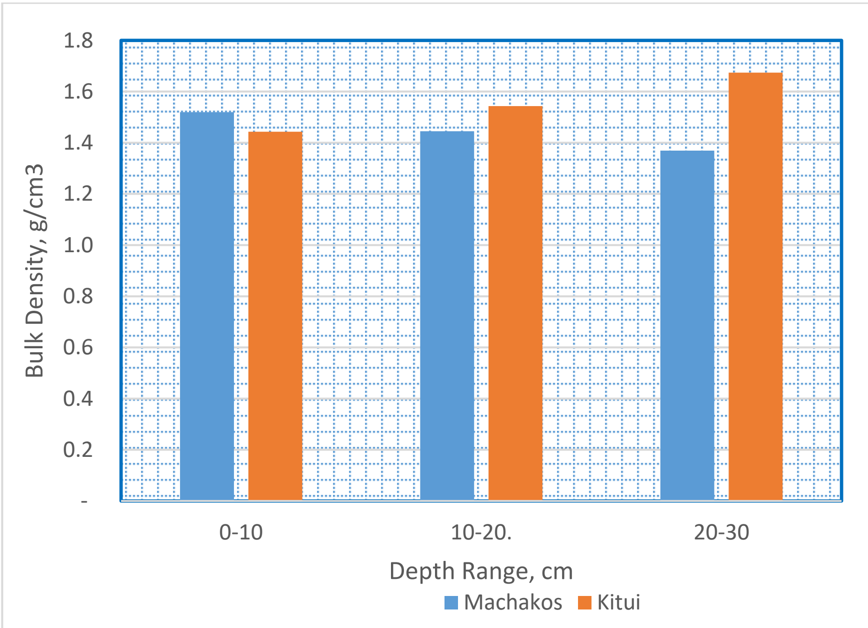

Figure 5-4 Soil bulk density for Experimental Sites

5.6 Penetration Resistance

Penetration resistance obtained at the experimental sites is presented in Table 5-6

Table 5-6 Penetration Resistance Data for the Experimental sites

Penetration Resistance (MPa)						
	Machakos			**Kitui**		
Depth(cm)	**0-10**	**10-20.**	**20-30**	**0-10**	10-20	20-30
1	5.29	5.45	4.68	5.34	5.47	5.73
2	5.75	5.47	5.67	5.82	5.84	5.70
3	5.81	5.77	5.61	5.48	5.61	5.82
4	5.46	4.85	5.55	5.46	5.68	5.82
5	5.62	5.50	5.69	4.81	5.63	5.85
6	5.62	5.50	5.69	5.70	5.79	5.80
7	5.34	5.39	5.65	5.49	5.79	4.98
8	5.59	5.17	4.90	5.08	5.86	5.69
9	4.87	5.03	5.63	5.05	5.69	5.67
Average	**5.48**	**5.34**	**5.45**	**5.35**	**5.71**	**5.67**

The penetration resistance of experimental field in Machakos decreased from 5.48 to 5.34Mpa between depths of 0-20 cm and increased to 5.45MPa between depths of 20-30cm. This is an indication of surface crusting and the existence of a hard pan/plough pan beyond 20cm. A different scenario was reported for the experimental field in Kitui. Between the depths of 0-20, cm penetration resistance increased from 5.35 to 5.71MPa indicating presence of a hardpan between depths of 10-20cm as represented in Figure 5-5.

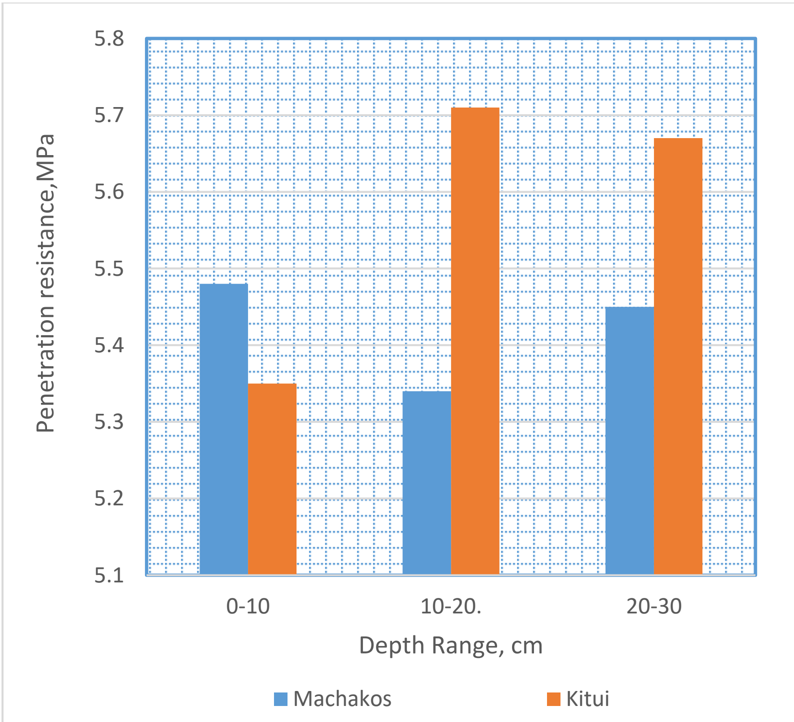

Figure 5-5 Soil penetration resistance for Experimental Sites

An increase in penetration resistance with tillage depth under different tillage implements has been reported by several researchers (Boydaş *et al.*, 2007; Mwangi *et al.*, 2018) However, Bengough and Mullins, (1990) and Vepraskas (1994) reported that for penetration resistance beyond 3MPa, plant root growth is considered slow. It is therefore evident that for both Machakos and Kitui experimental sites, the penetration resistance values are beyond this limit for the studied depth of 0-30cm and therefore at the two experimental site it is recommended that ripping is done using chisel ploughs to break the plough pan.

5.7 Moisture Content

Percentage moisture content increased with increase in depth between the ranges 0-30cm. for Kitui and Machakos experimental fields.

Table 5-7 Moisture data for the Experimental sites

Penetration Resistance (MPa)						
	Machakos			Kitui		
Depth(cm)	**0-10**	**10-20.**	**20-30**	**0-10**	**10-20**	**20-30**
1	1.79	2.92	3.61	8.89	4.43	10.71
2	3.43	7.28	9.63	3.00	7.76	9.54
3	5.28	6.90	8.34	4.28	8.26	15.26
4	2.76	9.48	12.21	4.86	8.40	10.41
5	2.26	7.52	8.93	2.86	6.42	6.95
6	4.86	8.59	10.05	3.40	7.95	9.82
7	3.63	7.94	10.91	4.07	6.46	7.52
8	3.31	7.70	14.14	2.43	3.32	5.00
9	4.51	10.34	11.65	3.58	8.66	11.31
Average	**3.53**	**7.63**	**9.94**	**4.15**	**6.85**	**9.61**

For Machakos experimental site, the moisture content increased from 3.53% at a depth of 0-10cm, to 7.63% at a depth of 10-20cm and to 9.94% at depths of 20-30cm. On the other hand, the moisture content increased from 4.15% at a depth of 0-10cm, to 6.85% at a depth of 10-20cm and to 9.61% at depths of 20-30cm for Kitui experimental site Figure 5-6. This was indicative of loose soil and existence of more voids at the depths of 20-30cm at the two experimental sites.

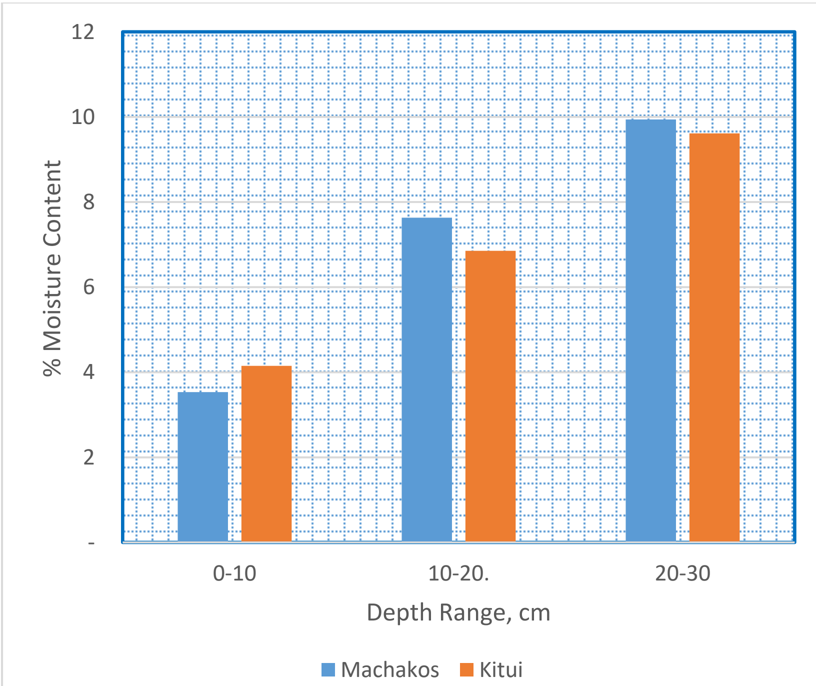

Figure 5-6 Percentage Soil Moisture for Experimental Site

According to Gong *et al.* (2003), soil columns tend to be drier at the top due to evaporation from the surface.

5.8 Effect of Depth on Specific Draft

Figures 5-7 and 5-8 represent the relationship between specific draft and tillage depth at given hitching length for Machakos and Kitui experimental sites respectively. In all the experimental sites, hitch length range of 2.5 to 3.5m was used. These lengths were sufficient and long enough to reduce interference between the animals and the implements during handling. Further short hitch lengths less than 2.5m would limit the penetration of the implement for it will lift up the hitch point and defeat the purpose of the experiment. Increased moisture in the lower horizons limits moisture available to plants with shallow roots.

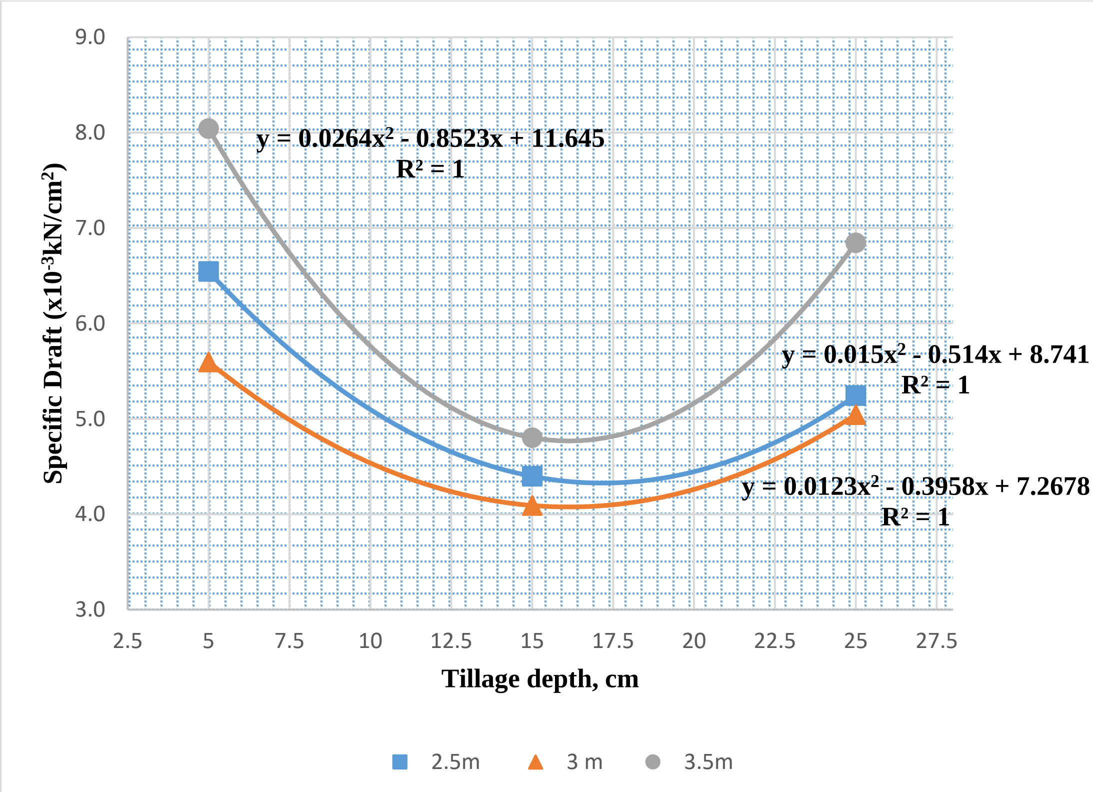

Figure 5-7 Specific Draft against tillage depth at different hitching length for Machakos Experimental Site

The results at Machakos experimental field indicated that the relationship between specific draft and tillage depth at different hitching length is a second order quadratic equation of the form; y = ax^2 - bx + c with the coefficient of determination (R^2) of 1.

Where;

y = Specific Draft, kN/cm^2

a & b = Scalar quantities

x = Tillage depth

c = y-intercept

The optimum tillage depth is given as x when the gradient of the curve y = ax^2 - bx + c is zero.

Therefore;

At a hitching length 2.5m;

$$\frac{dy}{dx} = 0 = 2(0.015)x - 0.514; x = 17.13cm$$

The specific draft is;

$$y = (0.015x17.13^2) - (0.514x17.13) + 8.741 = 4.34 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \text{ 43.4kN/m}^2$$

At a hitching length of 3m;

$$\frac{dy}{dx} = 0 = 2(0.0123)x - 0.3958; x = 16.1cm$$

The specific draft is;

$$y = (0.0123x16.1^2) - (0.3958x16.1) + 7.2678 = 4.08 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \text{ 40.8kN/m}^2$$

At a hitching length of 3.5m;

$$\frac{dy}{dx} = 0 = 2(0.0264)x - 0.8523; x = 16.14\ cm$$

The specific draft is;

$$y = (0.0264x16.14^2) - (0.8523x16.14) + 11.645 = 4.77 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \text{ 47.7kN/m}^2$$

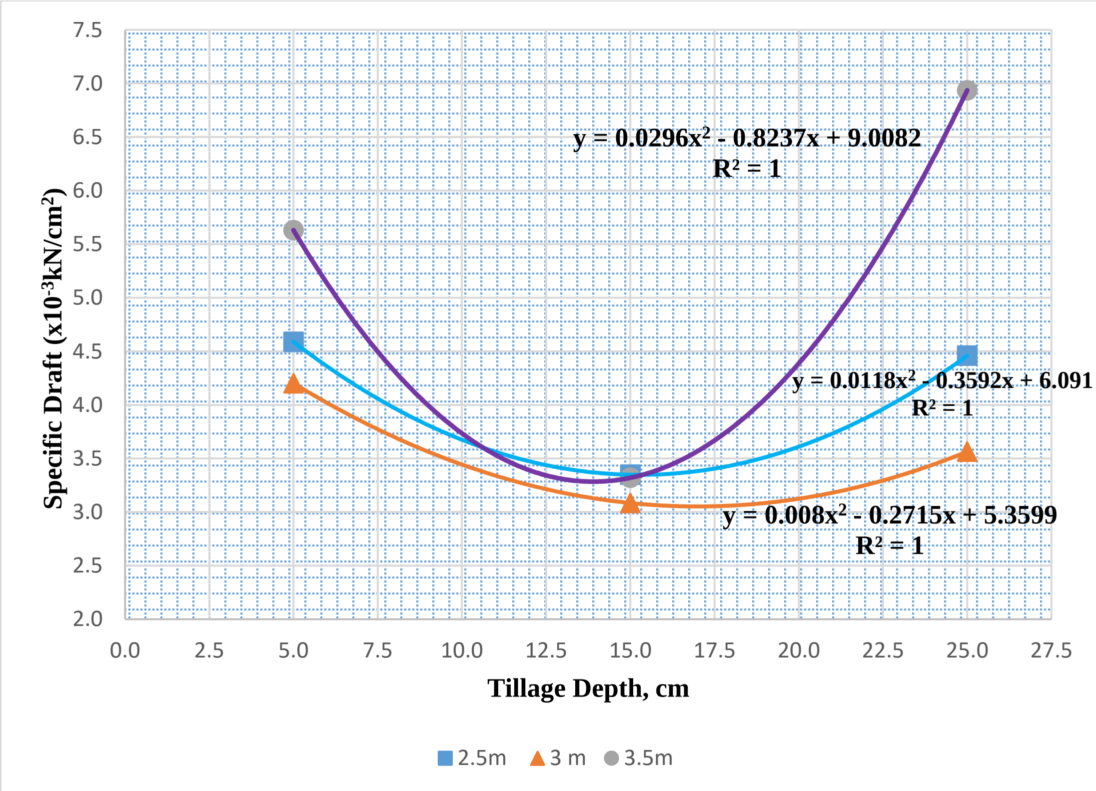

Figure 5-8 Specific Draft against tillage depth at different hitching length for Kitui Experimental Site

Similarly, for Kitui experimental site; the optimum tillage depth is given as;

At a hitching length 2.5m;

$$\frac{dy}{dx} = 0 = 2(0.0118x) - 0.3592; x = 15.22cm$$

The specific draft is;

$$y = (0.0118x15.22^2) - (0.3592x15.22) + 6.091 = 3.36 \text{ x } 10^{-3}\frac{\text{kN}}{\text{cm}^2} = 33.6 \text{ kN/m}^2$$

At a hitching length of 3m;

$$\frac{dy}{dx} = 0 = 2(0.008x) - 0.2715; x = 16.97cm$$

The specific draft is;

$$y = (0.008x16.97^2) - (0.2715x16.97) + 5.3599 = 3.06 \text{ x } 10^{-3}\frac{\text{kN}}{\text{cm}^2} = 30.6\text{kN/m}^2$$

At a hitching length of 3.5m;

$$\frac{dy}{dx} = 0 = 2(0.0296x) - 0.8237; x = 13.91\ cm$$

The specific draft is;

$$y = (0.0296x13.91^2) - (0.8237x13.91) + 9.0082 = 3.28 \text{ x } 10^{-3}\frac{\text{kN}}{\text{cm}^2} = 32.8\text{kN/m}^2$$

Table 5-8 Summary of optimum tillage depth and specific draft requirement at given hitching length

Hitching Length	**2.5m**		**3.0m**		**3.5m**	
	Machakos	**Kitui**	**Machakos**	**Kitui**	**Machakos**	**Kitui**
Optimum Depth (cm)	17.13	15.22	16.1	16.97	16.14	13.91
Optimum Specific Draft ($\mathbf{kN/m^2}$)	43.4	33.6	40.8	30.6	47.7	32.8

5.9 Effects of Hitching Length on Draft

Figures 5-9 and 5-10 represent the relationship between specific draft and hitching length at given tillage depths for Machakos and Kitui experimental sites respectively.

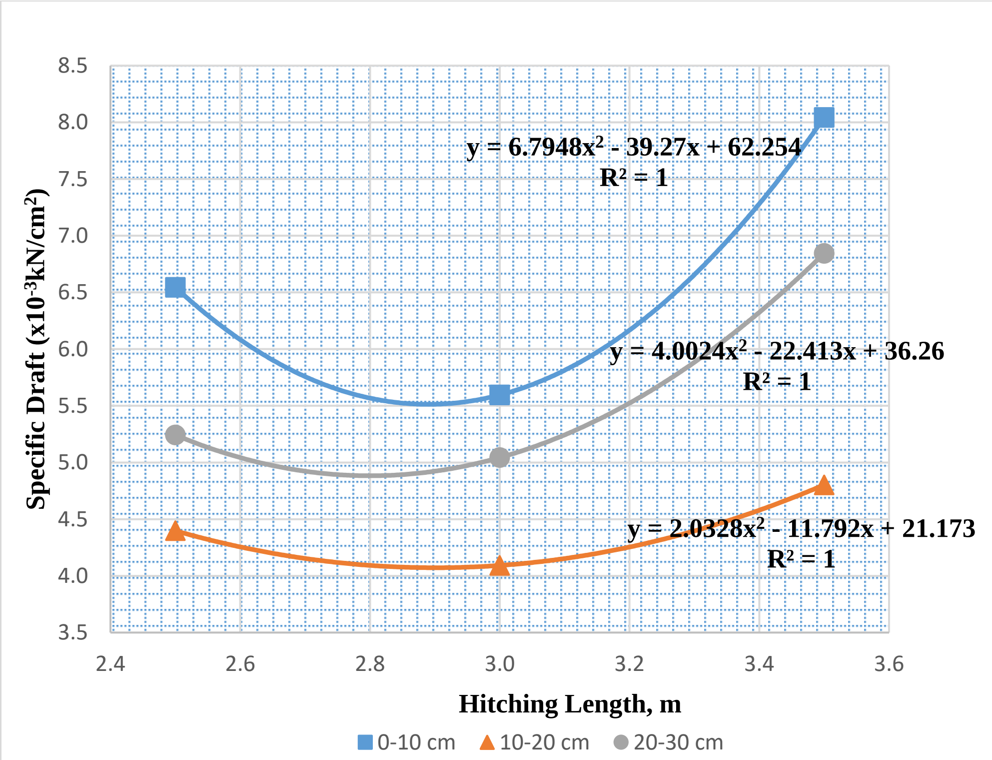

Figure 5-9 Specific Draft against hitching length at different tillage depth for Machakos Experimental Site

The results at Kitui experimental field indicated that the relationship between specific draft and tillage depth at different hitching length is a second order quadratic equation of the form; y = ax^2 - bx + c with the coefficient of determination (R^2) of 1.

The optimum hitching length is given as x; when the gradient of the curve y = ax^2 - bx + c is zero.

Therefore;

At a depth of 0-10cm;

$$\frac{dy}{dx} = 0 = 2(6.7948x) - 39.27; x = 2.89m$$

The specific draft is;

$$y = (6.7948x2.89^2) - (39.27x2.89) + 62.254 = 5.51 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \ 55.1\text{kN/m}^2$$

At a depth of 10-20cm;

$$\frac{dy}{dx} = 0 = 2(4.0024x) - 22.413; x = 2.8m$$

The specific draft is;

$$y = (4.0024x2.8^2) - (22.413x2.8) + 36.26 = 4.88 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \ 48.8\text{kN/m}^2$$

At a depth of 20-30cm;

$$\frac{dy}{dx} = 0 = 2(2.032x) - 11.792; x = 2.9m$$

The specific draft is;

$$y = (2.0328x2.9^2) - (11.792x2.9) + 21.173 = 4.07 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = \ 40.7\text{kN/m}^2$$

Similarly, for Kitui Experimental field;

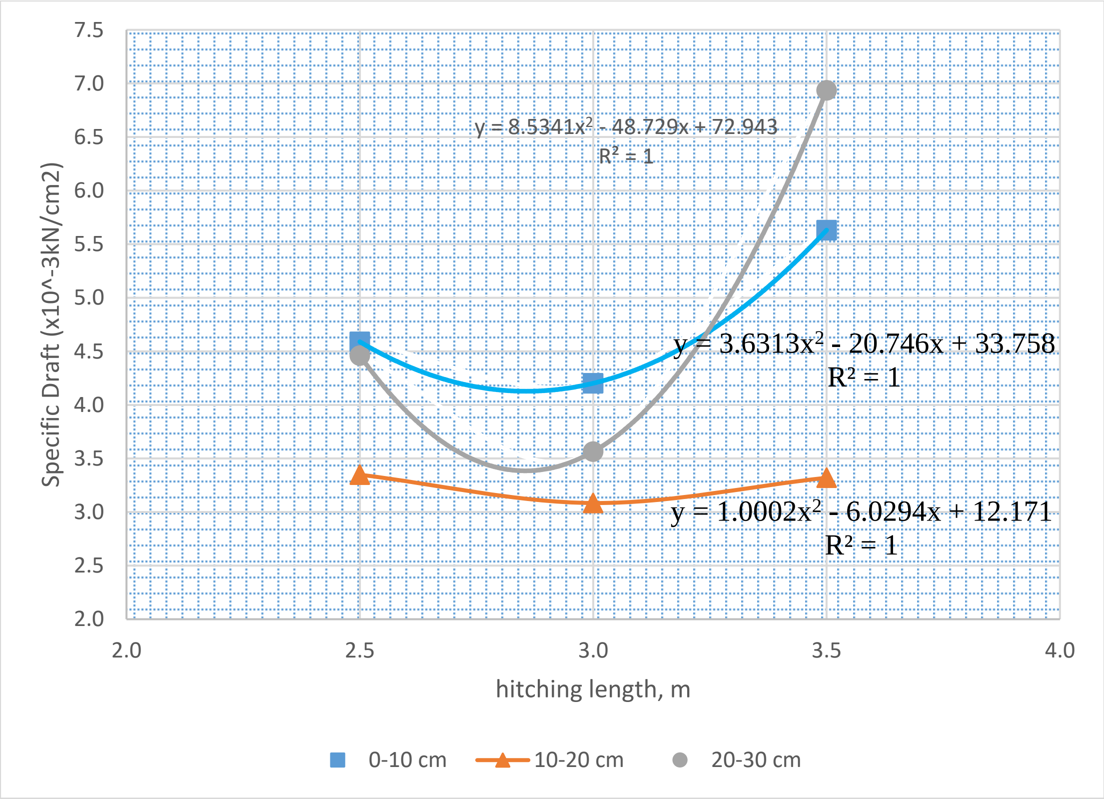

Figure 5-10 Specific Draft against hitching length at different tillage depth for Kitui Experimental Site

It indicated that the relationship between specific draft and hitching length at different tillage depth is a second order quadratic equation with the coefficient of determination (R^2) of 1. The optimum hitching length is given as;

At a depth of 0-10 cm;

$$\frac{dy}{dx} = 0 = 2(3.6313x) - 20.746; x = 2.86m$$

The specific draft is;

$$y = (3.6313x2.86^2) - (20.746x2.86) + 33.758 = 4.13 \text{ x } 10^{-3}\frac{\text{kN}}{\text{cm}^2} = \text{ 41.3 kN/m}^2$$

At a depth of 10-20 cm;

$$\frac{dy}{dx} = 0 = 2(1.002x) - 6.0294; x = 3.01m$$

The specific draft is;

$$y = (1.0002x3.01^2) - (6.029x3.01) + 12.171 = 3.09 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = 30.9 \text{ kN/m}^2$$

At a depth of 20-30 cm;

$$\frac{dy}{dx} = 0 = 2(8.5341x) - 48.729; x = 2.85m$$

The specific draft is;

$$y = (8.5341x2.85^2) - (48.729x2.85) + 72.943 = 3.38 \text{ x } 10^{-3}\,\frac{\text{kN}}{\text{cm}^2} = 33.8\text{kN/m}^2$$

Table 5-9 Summary of optimum hitching length and specific draft requirement at given tillage depth

Tillage Depth	**0-10cm**		**10-20cm**		**20-30cm**	
	Machakos	**Kitui**	**Machakos**	**Kitui**	**Machakos**	**Kitui**
Optimal Hitching Length (m)	2.89	2.86	2.80	3.01	2.90	2.85
Optimum Specific Draft ($\mathbf{kN/m^2}$)	55.1	41.3	48.8	30.9	40.7	33.8

According to Harrigan and Roosenberg (2002), well-conditioned oxen are capable of working draft loads measured as tension (kg-force, kN) equal to 10-12% of their body weight throughout the day and greater loads for short periods of time. Therefore, two oxen of average weight 250 kg each (1 Tropical Livestock Unit) can generate a draft force of 500 - 600 N for normal pull or towing. At the experimental sites the bulls used weighed on average 250-300kg each and this produced an average specific draft of 28kN/m^2 - 40.7kN/m^2.

Average specific draft at different tillage depths and hitching length were subjected to Analysis of Variance (ANOVA) Table 5-10 and 5-11 for Machakos and Kitui experimental sites respectively at 95% confidence level (P>0.05). The following hypothesis were tested;

For **tillage depth**;

Ho: $\mu 0\text{-}10 = \mu 10\text{-}20 = \mu 20\text{-}30$

H1: $\mu 0\text{-}10 \neq \mu 10\text{-}20 \neq \mu 20\text{-}30$

For **hitching length**;

Ho: $\mu 2.5 = \mu 3 = \mu 3.5$

H1: $\mu 2.5 \neq \mu 3 \neq \mu 3.5$

Table 5-10 Machakos Experimental Site Specific Draft Summary

Machakos ANOVA							
	SUMMARY	**Count**	**Sum**		**Average**		**Variance**
	0-10cm	3	20.18402		6.728008		1.522888
	10-20cm	3	13.29262		4.430872		0.127045
	20-30cm	3	17.13099		5.710329		0.974999
	2.5m	3	16.18619		5.395396		1.170132
	3 m	3	14.73088		4.910293		0.578375
	3.5m	3	19.69056		6.56352		2.684681
	ANOVA						
	Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
	Tillage Depth	7.949513	2	3.974756	17.34065	0.010693	6.944272
	Hitching Length	4.332998	2	2.166499	9.451775	0.030501	6.944272
	Error	0.916864	4	0.229216			
	Total	13.19937	8				
Remarks	H_o: $\mu_{0\text{-}10} = \mu_{10\text{-}20} = \mu_{20\text{-}30}$ H1: $\mu_{0\text{-}10} \neq \mu_{10\text{-}20} \neq \mu_{20\text{-}30}$ H_o: $\mu_{2.5} = \mu_3 = \mu_{3.2}$ H1: $\mu_{2.5} \neq \mu_3 \neq \mu_{3.5}$						

From Table 5-10, the specific draft results for Machakos Experimental has significant difference across the different tillage depth as well as for different hitching lengths. The P-values obtained through ANOVA analysis are 0.010693and 0.030501 for tillage depth and hitching length respectively, which is, less than 0.05. The conclusion made therefore is that specific draft varies significantly with changing tillage depth and hitching length for Machakos experimental site.

Table 5-11 Kitui Experimental Site Specific Draft Summary

Kitui ANOVA							
	SUMMARY	**Count**	**Sum**		**Average**		**Variance**
	0-10cm	3	14.42157		4.807189		0.545998
	10-20cm	3	9.753063		3.251021		0.021041
	20-30cm	3	14.96017		4.986722		3.05001
	2.5m	3	12.39738		4.132461		0.465047
	3 m	3	10.85067		3.616889		0.314354
	3.5m	3	15.88675		5.295582		3.352586
	ANOVA						
	Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
	Tillage Depth	5.466549	2	2.733275	3.908274	0.1145879	6.944272
	Hitching Length	4.436674	2	2.218337	3.171971	0.1495367	6.944272
	Error	2.797424	4	0.699356			
	Total	12.70065	8				
Remarks	H_o: $\mu_{0-10} = \mu_{10-20} = \mu_{20-30}$ H1: $\mu_{0-10} \neq \mu_{10-20} \neq \mu_{20-30}$ H_o: $\mu_{2.5} = \mu_3 = \mu_{3.2}$ H1: $\mu_{2.5} \neq \mu_3 \neq \mu_{3.5}$						

However, a different scenario was reported for Kitui experimental site. No statistically significant difference was reported for specific draft at different tillage depths and hitching lengths. The P values obtained were 0.1145879 and 0.1495367 for tillage depth and hitching length respectively Table 5-11. These values are greater than 0.05 and therefore specific draft does not vary significantly with changing tillage depth and hitching length for Kitui experimental site.

5.10 Summary of the findings

At the experimental fields, the bulk density varied from 1.52 to 1.37g/cm3 and 1.44 to 1.67g/cm3 for Machakos and Kitui sites respectively.

The moisture content increased with increase in depth at the two experimental sites ranging from 3.53 to 9.94% for Machakos site and from 4.15 to 9.61% for Kitui site.

Soil shear strength parameters ranged between 21.71 and 29.6kPa between depths of 0-20cm and then decreased to 28.07kPa for Machakos experimental site. In Kitui experimental site, shear strength parameters ranged between 30.02 and 39.29kPa between depths of 0 and 30cm.

The relationship obtained between specific draft and depth at particular hitching length as well as specific draft against hitching length is a second order quadratic model of the form $y = ax^2 + bx + c$. The optimal hitching length and tillage depth for Machakos experimental site was obtained as 2.9m (~3m) and 16.5 (~17) cm respectively. In Kitui experimental site, the optimal hitching length was obtained as 2.9 m (~3m) and the optimal tillage depth was 15.4 cm.

The specific draft results for Machakos Experimental has significant difference across the different tillage depth as well as for different hitching lengths. This indicated the importance of using optimized hitching length and tillage depth since slight change in any of the two parameters results in an increased energy requirement/tillage cost. However, no statistically significant difference was reported for specific draft at different tillage depths and hitching lengths for Kitui experimental site and therefore any other the depths and hitching lengths studied can be used during tillage. Nevertheless, tillage depth would affect root development and therefore very shallow depths should be avoided.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The two sites Machakos and Kitui were found to have similar soils types' i.e. sandy Clay Loamy soils. Notable at the two sites was the existence of hardpan at various levels. This is well collaborated by the determined values of the bulk density, penetration resistance and shear strength at the two sites. It was also notable that beyond the depths of 20-30cm the soil was loosening, hence existence of more voids, which has been collaborated by high Percentage (%) of moisture content.

The study established that the relationship between the specific draft, tillage depth and hitch length was a second order quadratic equation of the form $y = ax^2 - bx + c$ with the coefficient of determination (R^2) of 1 at the Machakos and Kitui experimental sites.

Where;

y = Specific Draft, kN/cm^2
a & b = scalar quantities
x = Tillage depth
c = y-intercept

After optimization of the above model, it was found that the optimum average tillage depth was 16cm, at the optimum hitch length of 3m when an average specific draft of $41kN/m^2$ was applied at normal oxen operating rate in a sandy clay loamy soils using an animal drawn sub-soiler. Analysis of variance (ANOVA) was carried for the results of Specific draft hitch length and tillage depth for the two experimental sites. The analysis established that specific draft varies significantly with changing tillage depth and hitching length for Machakos experimental site while for Kitui there was no significant difference and this is attributed to the shear strength characteristics.

Based on this study is can be concluded that the optimum hitching length when using oxen drawn tillage implements is 3.0m which can give an optimum furrow depth of 16cm. This depth is sufficient to allow root growth for most of the crops grown in the ASAL regions.

6.2 Recommendations

The following recommendations are hereby made based on the results at the experimental sites; For further studies,

1) The use of minimum tillage equipment in ASAL has not been wide spread. It is recommended that other animal drawn tillage equipment namely ripper and Chisel can be used in similar soils to compare the optimum depths and hitch length that can be achieved for the results will have a strong bearing towards removal of soil hardpan, which inhibits water infiltration and reduces. Notable at the experimental sites it was evident there was soil crusting or hardpan that was collaborated by the values of penetration resistance.
2) This study should be carried out in other soil types to establish whether the optimal parameters, tillage depth, hitch length and specific draft can be achieved using an animal drawn sub-soiler.

The study also recommends as follows for adoption by the farmers;

1) Use of a sub-soiler hitched on an optimum hitch length of 3.0m, which can generate an optimum furrow depth of 16cm when using two oxen weighing about 300kg each in a sandy clay loam soils.
2) In order to allow effective root development there is need to rip or carry out sub soiling with deep penetration tillage implements to break the hard pan. Further farmers in at the two sites and in the environ where the soils are similar are advised to plough at the appropriate soil moisture content to allow implement penetration as a coping mechanism for handling hard pan challenges.

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APPENDICES

Appendix A: Soil Classification

Table 8-1 Soil Classification for Machakos Experimental Sites

Sample No:	Depth	H_1	T_1	H_2	T_2	% Sand	% Clay	% Silt	Soil Class
	0-10	16	22.2	13	22.2	68	26	6	Sandy clay loam
	10-20.	11	22.2	10	22.2	78	20	2	Sandy loam/Sandy clay loam
	20-30	11.5	22.2	10	22.2	77	20	3	Sandy loam
	0-10	13	22.2	11	22.2	74	22	4	Sandy clay loam
	10-20.	17	22.2	15	22.2	66	30	4	Sandy clay loam
	20-30	17.5	22.2	16	22.2	65	32	3	Sandy clay loam
	0-10	20	22.2	17.5	22.2	60	35	5	Sandy clay/Sandy clay loam
	10-20.	22	22.2	21	22.2	56	42	2	Sandy clay
	20-30	25	22.2	21.5	22.2	50	43	7	Sandy clay

Table 8-2 Soil Classification for Kitui Experimental Sites

Sample No.	Depth	H 1	T 1	H 2	T 2	% Sand	% Clay	% Silt	Soil Class
	0-10	19	20.8	14	20	61	26	12	Sandy clay loam
	10-20.	19	20.8	15	20	61	28	10	Sandy clay loam
	20-30	22	20.8	17	20	55	32	12	Sandy clay loam
	0-10	18	20.8	9	20	63	16	20	Sandy loam
	10-20.	16	20.8	14	20	67	26	6	Sandy clay loam
	20-30	17	20.8	15	20	65	28	6	Sandy clay loam
	0-10	16	20.8	12	20	67	22	10	Sandy clay loam
	10-20.	18	20.8	15.5	20	63	29	7	Sandy clay loam
	20-30	20	20.8	17.5	20	59	33	7	Sandy clay loam

Appendix B: Laboratory Shear Strength

Appendix B1: Triaxial Curves

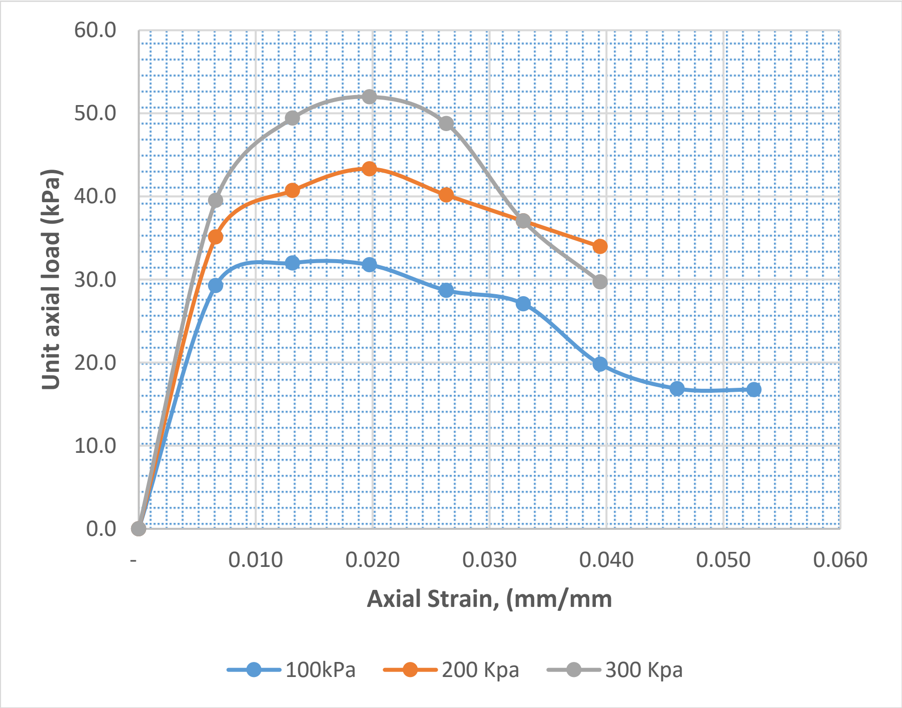

Figure 8-1 Graph of Unit axial load versus Axial Strain for Sample 1 at Machakos Experimental Site

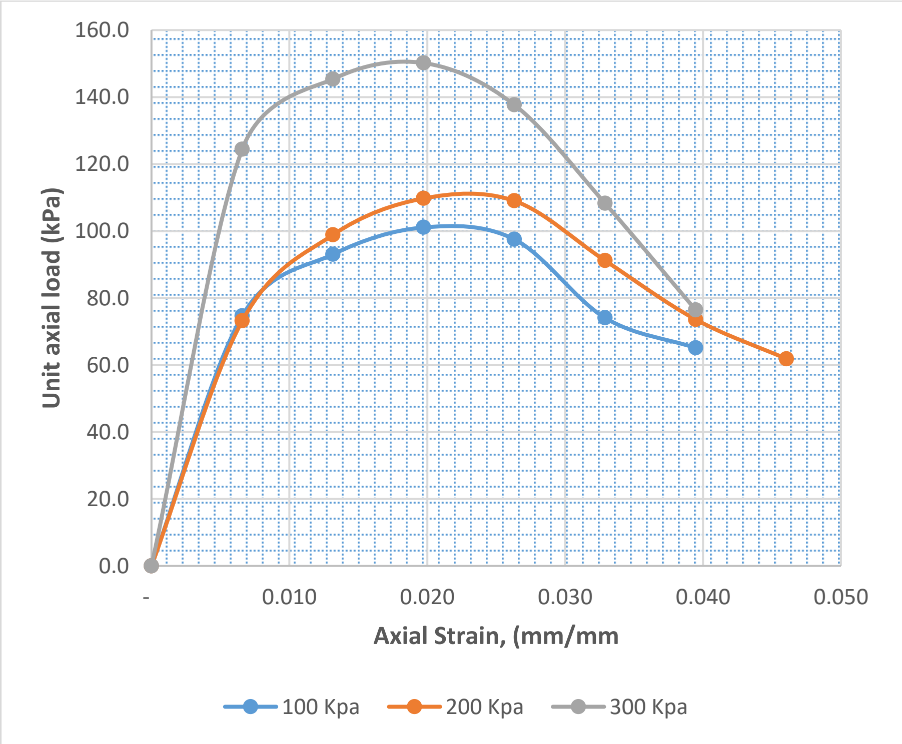

Figure 8-2 Graph of Unit axial load versus Axial Strain for Sample 2 at Machakos Experimental Site

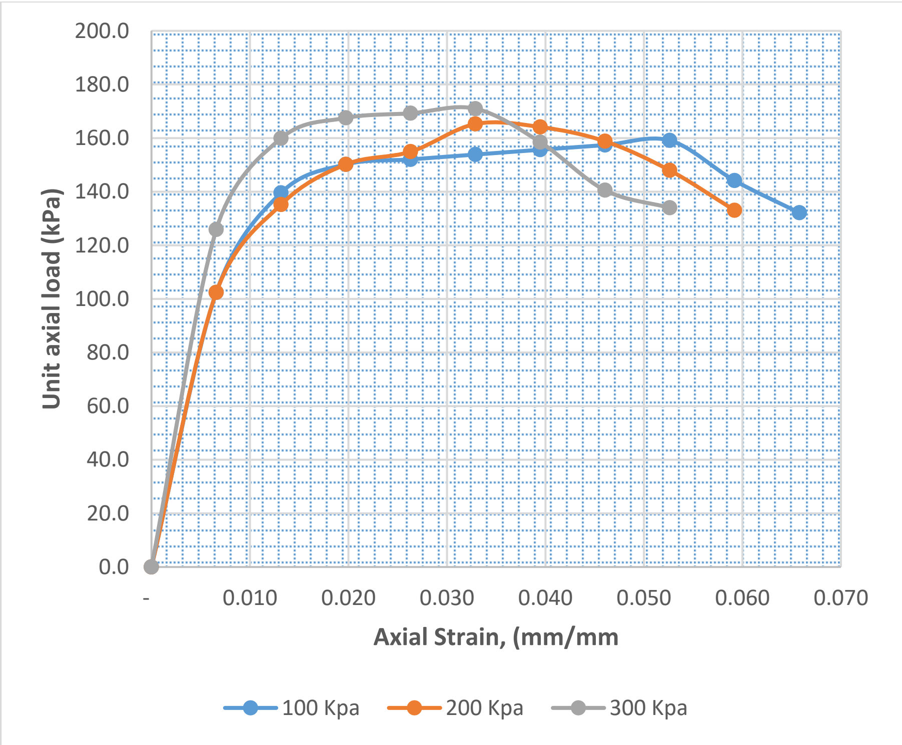

Figure 8-3 Graph of Unit axial load versus Axial Strain for Sample 3 at Machakos Experimental Site

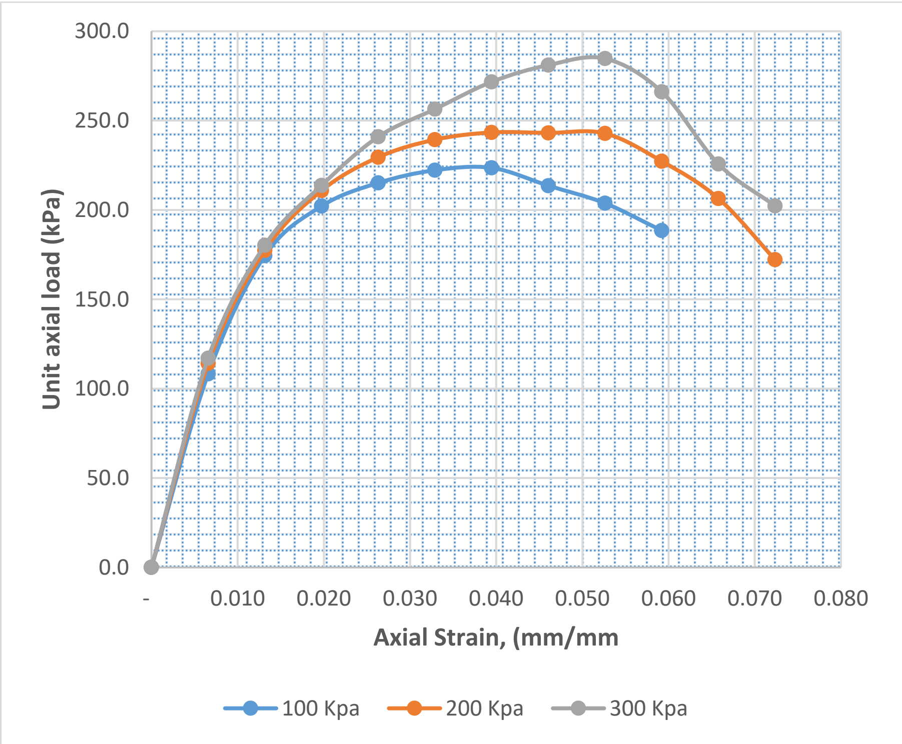

Figure 8-4 Graph of Unit axial load versus Axial Strain for Sample 1 at Kitui Experimental Site

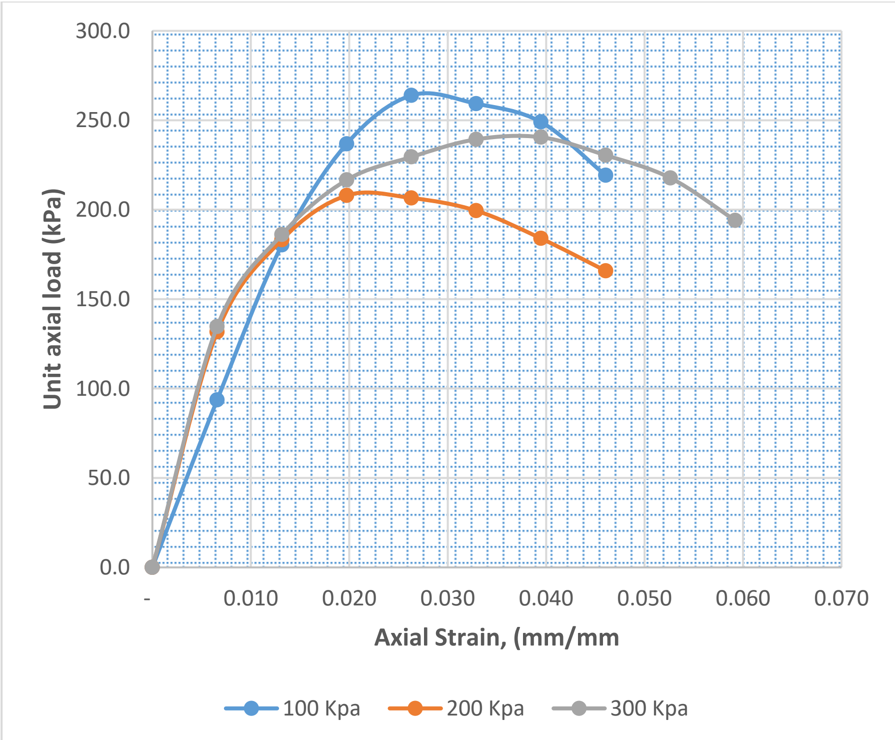

Figure 8-5 Graph of Unit axial load versus Axial Strain for Sample 2 at Kitui Experimental Site

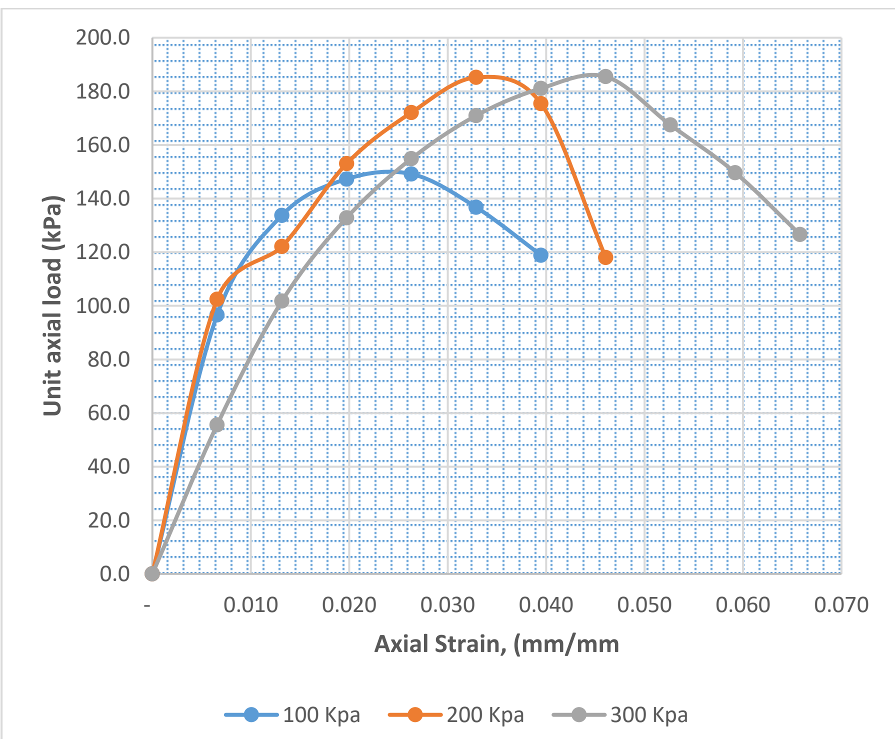

Figure 8-6 Graph of Unit axial load versus Axial Strain for Sample 3 at Kitui Experimental Site

Appendix B2: Major and Minor Stresses

Table 8-3 Major and Minor Principal stress of soil sample from the Experimental Field

Sample No.	Minor Principal Stress, δ3 (kPa)	Unit Axial Load at Failure, ΔP (kPa)		Major principal Stress, δ1 (kPa)	
		Machakos	Kitui	Machakos	Kitui
1	100	145.2	266.3	245.2	366.3
	200	272.9	462.1	472.9	662.1
	300	402.4	670.8	702.4	970.8
2	100	101.079	211.1	201.079	311.1
	200	197.5	398.4	397.5	598.4
	300	265.7	481.1	565.7	781.1
3	100	200.5	214.8	300.5	314.8
	200	339.1	403.2	539.1	603.2
	300	510.4	613.5	810.4	913.5

Appendix B3: Mohr Circle

Machakos County Experimental Site

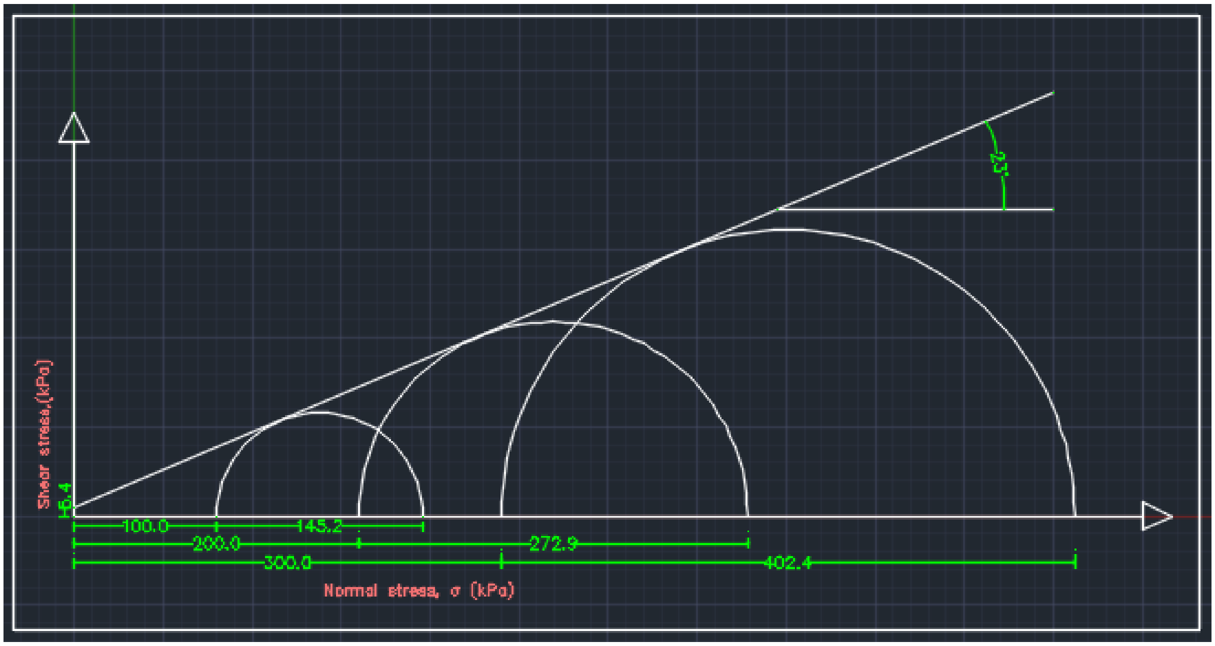

Figure 8-7 Mohr Circle for Sample 1 (Machakos Experimental Site)

Figure 8-8 Mohr Circle for Sample 2 (Machakos Experimental Site)

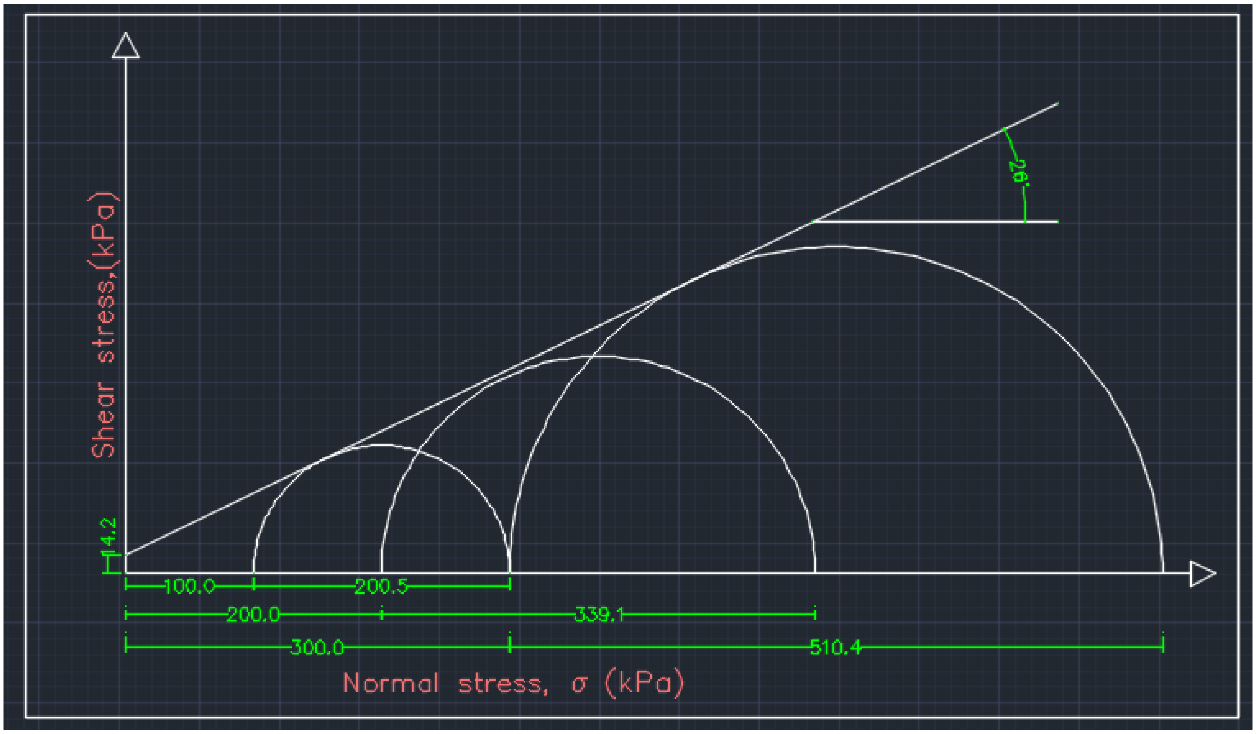

Figure 8-9 Mohr Circle for Sample 3 (Machakos Experimental Site)

Kitui County Experimental Site

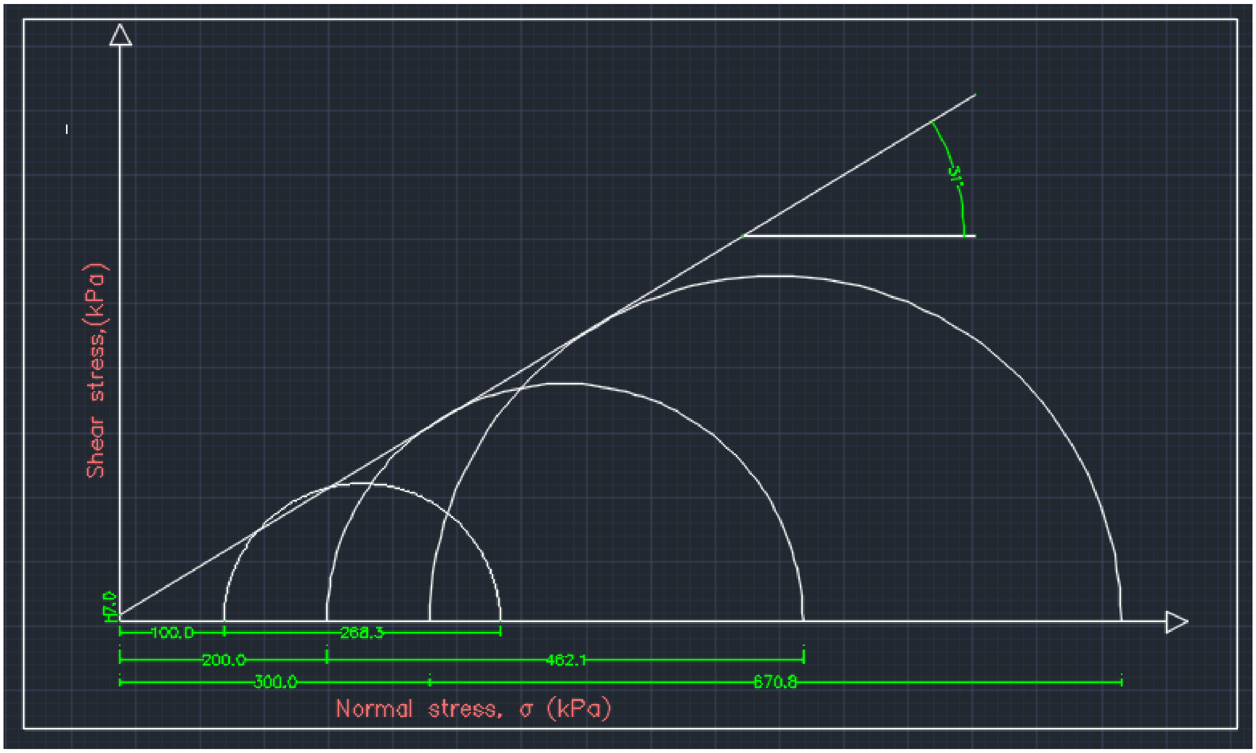

Figure 8-10 Mohr Circle for Sample 1 (Kitui Experimental Site)

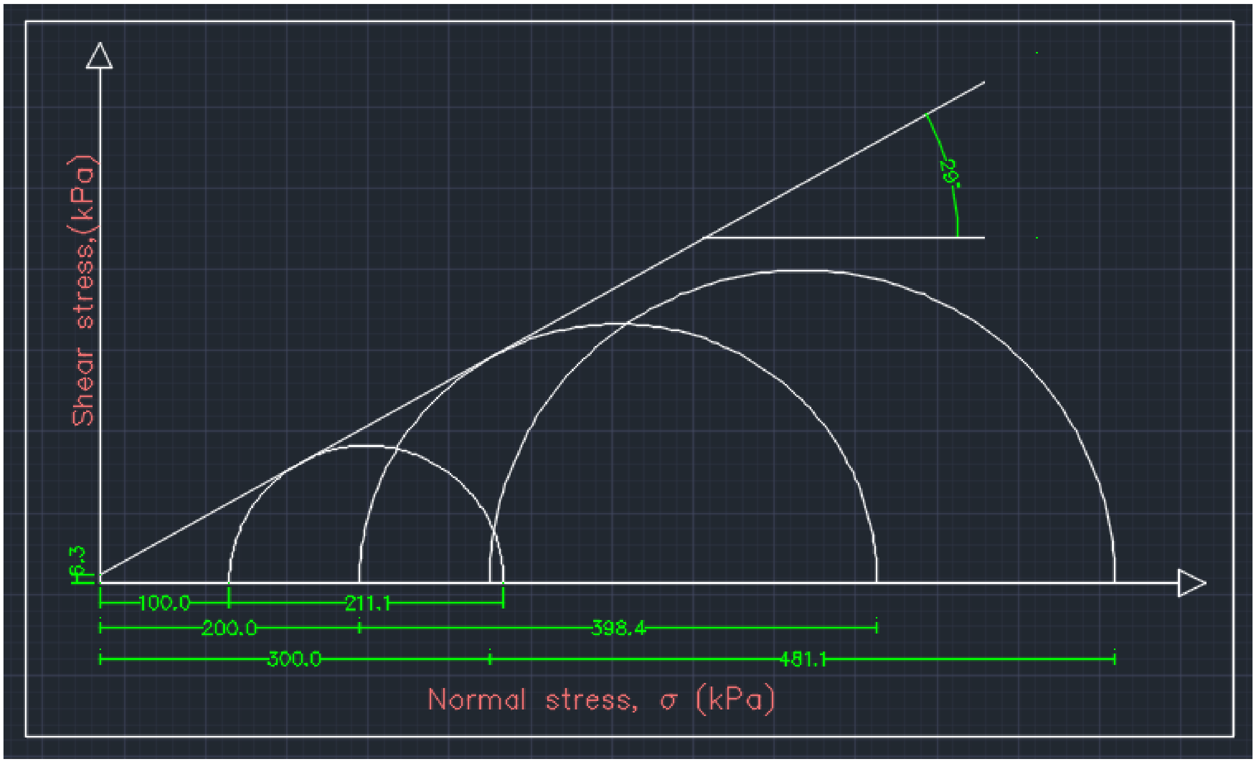

Figure 8-11 Mohr Circle for Sample 2 (Kitui Experimental Site)

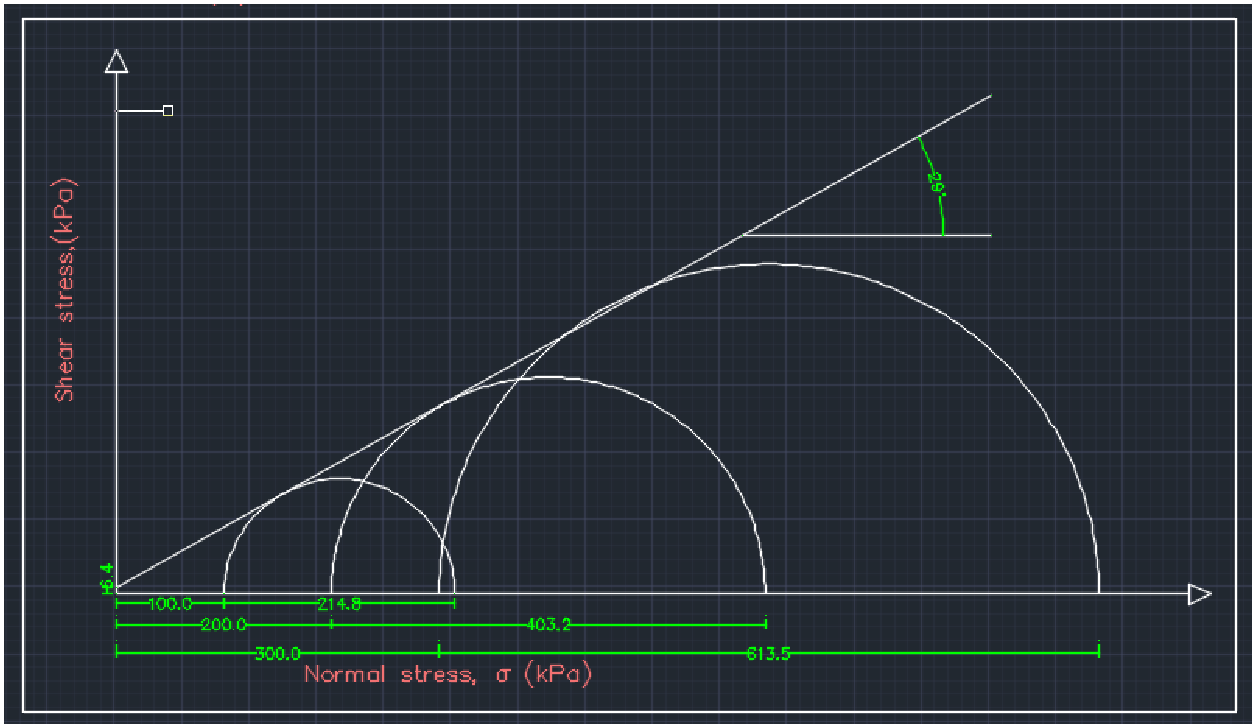

Figure 8-12 Mohr Circle for Sample 3 (Kitui Experimental Site)

Appendix C: In-Situ Shear Strength

Table 8-4 Shear strength Data for Machakos Experimental Site

Plot No.	Depth	Cohesion	Minor Principal Stress (psi), δ3			Average	Phi (Φ)	Tan (Φ)	Shear Strength
		(Kpa)	5psi	10psi	15psi	(Kpa)	Degrees)		
1	0-10cm	1.72	1.9	2.6	3.7	18.85	15	0.268	6.770
	10-20cm	4.827	2.9	5.2	6.4	33.32	24.5	0.456	20.014
	20-30cm	1.72	2.3	4.4	6.4	30.11	23.5	0.435	14.811
2	0-10cm	5.17	2.3	3.5	5.6	26.20	17.5	0.315	13.431
	10-20cm	9.31	3.6	6	8.1	40.68	24.5	0.456	27.849
	20-30cm	6.21	3.4	5.9	8.3	40.45	25.5	0.477	25.503
3	0-10cm	4.48	3.7	6.7	9.7	46.19	30	0.577	31.151
	10-20cm	8.96	3.6	5.9	8.73	41.90	25	0.466	28.497
	20-30cm	8.62	3.6	5.3	8	38.84	25	0.466	26.732
4	0-10cm	5.52	3.3	6.1	8	39.99	27	0.510	25.896
	10-20cm	9.65	4.1	6.9	9.8	47.80	28.5	0.543	35.605
	20-30cm	7.93	3.5	6.1	8.7	42.06	27.5	0.521	29.824
5	0-10cm	4.48	3.3	6.4	8.5	41.83	27	0.510	25.793
	10-20cm	3.79	3.1	5.7	8.1	38.84	29	0.554	25.320
	20-30cm	3.79	3.3	6.1	8.8	41.83	29	0.554	26.976
6	0-10cm	6.21	2.6	4.2	5.8	28.96	17.5	0.315	15.340
	10-20cm	8.24	4.3	7.3	10.2	50.10	30.5	0.589	37.752
	20-30cm	6.7	3.7	6.4	8.9	43.67	28	0.532	29.918
7	0-10cm	7.93	3.4	5.6	7.9	38.84	24	0.445	25.223
	10-20cm	6.56	3.9	6.8	9.8	47.11	30.5	0.589	34.312
	20-30cm	5.86	3.5	6.1	8.7	42.06	28.5	0.543	28.696
8	0-10cm	9.31	3.8	5.8	7.6	39.53	21	0.384	24.484
	10-20cm	9.65	3.5	5.6	7.7	38.61	23.5	0.435	26.438
	20-30cm	9.65	4.2	7.3	10.2	49.87	31	0.601	39.616
9	0-10cm	3.45	4.3	6	8.8	43.90	28.5	0.543	27.284
	10-20cm	8.24	3.7	6.4	9	43.90	27	0.510	30.606
	20-30cm	6.21	3.7	6.5	9.3	44.82	28.5	0.543	30.543

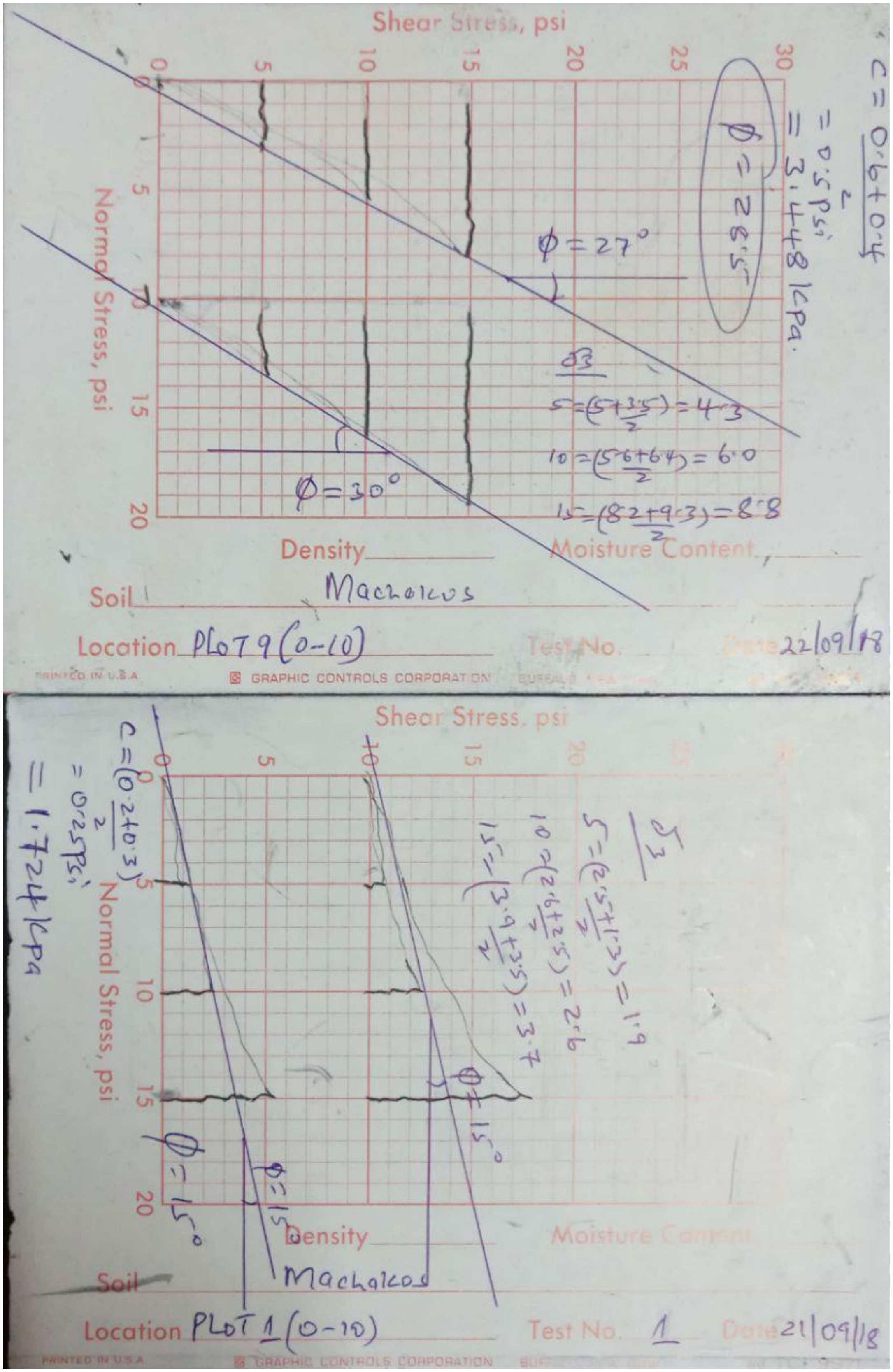

Figure 8-13 In-situ Shear stress versus Normal stress curves for Machakos Experimental Plot

Table 8-5 Shear strength Data for Kitui Experimental Site

Plot No.	Depth	Cohesion	Minor Principal Stress (psi), δ3			Average	Phi (Φ)	Tan (Φ)	Shear Strength
		(Kpa)	5psi	10psi	15psi	(Kpa)	Degrees)		
1	0-10cm	6.55	3.4	5.9	8.5	40.91	27.5	0.521	27.846
	10-20cm	7.93	3.6	6.3	9	43.44	27.5	0.521	30.542
	20-30cm	7.24	4.3	7.8	8.1	46.42	35	0.700	39.747
2	0-10cm	9.31	6.5	7	9.7	53.32	28.5	0.543	38.260
	10-20cm	4.14	2.7	4.6	6.7	32.18	22	0.404	17.140
	20-30cm	4.83	4.2	7.9	11.7	54.70	35	0.700	43.130
3	0-10cm	6.55	3.9	7.8	10.6	51.25	27.5	0.521	33.230
	10-20cm	7.93	3.4	6.1	8.7	41.83	27.5	0.521	29.704
	20-30cm	12.76	4.8	7.8	10.9	54.01	31	0.601	45.212
4	0-10cm	6.21	3.6	6.3	9	43.44	28.5	0.543	29.794
	10-20cm	5.86	4.5	8.1	11.6	55.62	32	0.625	40.614
	20-30cm	6.22	3.4	5.9	8.4	40.68	27	0.510	26.947
5	0-10cm	7.24	3.4	5.9	8.4	40.68	26.5	0.499	27.522
	10-20cm	9.65	4.4	7.4	10.4	51.02	30.5	0.589	39.704
	20-30cm	20.34	5.4	8	10	53.78	27.5	0.521	48.336
						0.00			
6	0-10cm	5.52	2.9	5.1	7.4	35.39	24	0.445	21.278
	10-20cm	3.79	3.1	5.7	8.3	39.30	27	0.510	23.814
	20-30cm	7.55	4.1	7.2	10.4	49.87	31.5	0.613	38.112
7	0-10cm	14.82	4.6	7.2	9.6	49.18	27.5	0.521	40.423
	10-20cm	5.86	4.2	7.8	11.4	53.78	35	0.700	43.517
	20-30cm	4.83	4.4	7.8	11.4	54.24	36	0.727	44.237
						0.00			
8	0-10cm	6.55	3.6	6.1	8.8	42.52	27	0.510	28.214
	10-20cm	3.79	3.5	6.5	9.5	44.82	31	0.601	30.718
	20-30cm	6.55	3.9	6.8	9.6	46.65	29	0.554	32.411
9	0-10cm	3.44	2.9	5.1	7.5	35.62	29.5	0.566	23.594
	10-20cm	8.96	4.4	7.8	10.3	51.71	31	0.601	40.031
	20-30cm	5.52	4.1	7.4	8.2	45.28	33.5	0.662	35.487

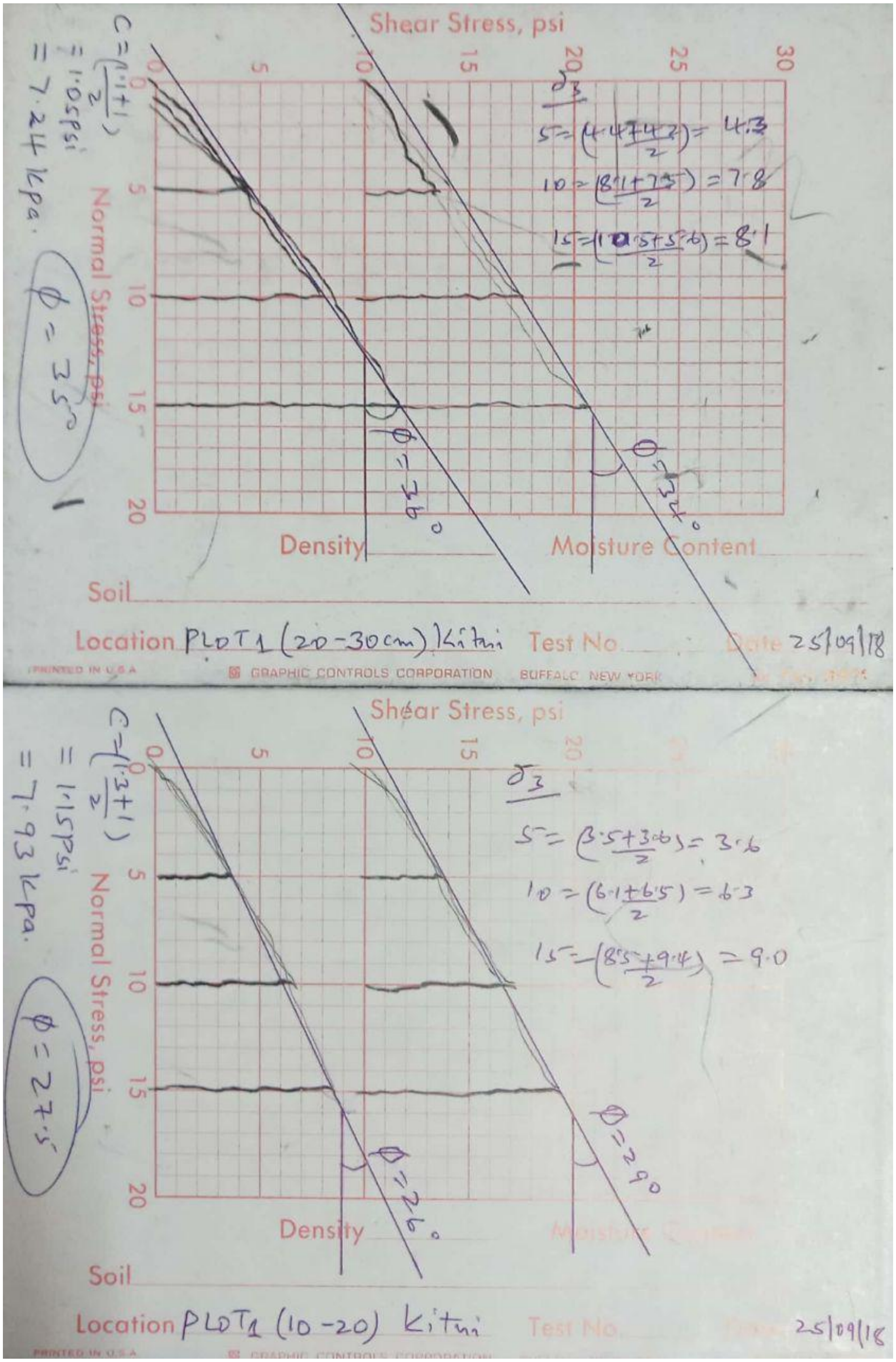

Figure 8-14 In-situ Shear stress versus Normal stress curves for Kitui Experimental Plot

Appendix D: Draft Data

Table 8-6 Draft Data at 2.5m hitching length for Machakos Experimental Site

	Hitching length = 2.5m								
	Plot 1	**Plot 1**	**Plot 1**	**Plot 2**	**Plot 2**	**Plot 2**	**Plot 3**	**Plot 3**	**Plot 3**
	0-10	**10_20**	**20-30**	**0-10**	**10_20**	**20-30**	**0-10**	**10_20**	**20-30**
	1.22	1.32	1.80	1.48	1.04	1.78	0.66	1.46	1.14
	1.12	1.36	1.74	1.50	1.18	1.84	0.98	1.48	1.36
	1.10	1.48	1.78	1.44	1.26	1.78	1.06	1.58	1.40
	1.06	1.52	1.92	1.46	1.16	1.90	1.04	1.54	1.72
	1.24	1.36	1.90	1.20	1.14	2.22	0.98	1.50	2.02
	1.30	1.48	1.88	1.02	1.16	2.64	1.08	1.64	2.26
	1.18	1.32	1.89	1.36	1.10	2.30	0.94	1.52	2.22
	1.22	1.40	1.78	0.92	1.18	2.74	0.62	1.22	1.92
	1.02	1.44	1.62	1.32	1.20	2.58	0.66	1.50	1.16
	1.30	1.54	1.64	1.48	1.09	2.56	0.60	1.30	1.52
	1.14	1.52	1.68	1.62	1.08	2.66	0.84	1.26	1.94
	0.88	1.54	1.62	1.38	1.12	2.62	0.62	1.34	1.70
	0.86	1.48	1.64	1.30	1.18	2.58	0.74	1.30	2.46
	1.04	1.30	1.52	1.44	1.06	2.56	0.84	1.26	2.72
	1.32	1.24	1.46	1.28	1.02	2.40	0.80	1.16	2.56
	1.10	1.48	1.44	1.24	1.14	2.30	0.92	1.26	2.50
	1.06	1.44	1.42	1.32	1.16	2.24	0.98	1.28	2.12
	1.20	1.48	1.46	1.20	1.18	2.34	0.90	1.24	2.22
	1.18	1.34	1.40	1.14	1.14	2.40	1.06	1.10	2.14
	1.06	1.36	1.54	1.10	1.04	2.52	1.12	1.06	2.28
	1.30	1.26	1.64	1.16	1.08	2.22	1.02	0.98	2.78
	1.38	1.20	1.46	0.90	0.94	2.38	1.34	0.92	2.54
	1.10	1.52	1.34	1.12	1.02	2.20	1.20	1.08	1.48
	1.32	1.22	1.60	1.14	0.96	2.24	1.06	1.00	
	1.40	1.14	1.46	1.16	1.08	1.86	1.00	0.96	1.86
	1.16	0.98	1.42	1.26	1.12		1.14	1.04	2.12
	1.28	1.08	1.34	1.14	1.32		1.16	1.08	2.70
	1.22	1.32	1.32	1.28	1.12		1.08	1.18	2.24
	1.36	1.22	1.46	1.14	1.14		1.22	1.40	2.40
	1.40	1.18	1.42	1.28	1.16		1.28	0.98	2.82
	1.35	1.20	1.40	1.46	1.30		1.22	1.48	2.96
	1.28	1.00	1.42	1.20	1.32		1.02	1.54	2.46
	1.16		1.46	1.08	1.20		0.82	1.44	3.10
	1.28		1.52	1.20	1.34			1.42	
	1.40		1.42	0.92	1.30			1.46	
	1.18		1.30	1.04				1.44	
	1.14		1.20	0.86				1.30	
	1.38			1.02				1.14	
	1.26			1.20					
	1.22			1.18					
	1.14			1.06					
Average	**1.20**	**1.34**	**1.55**	**1.22**	**1.14**	**2.31**	**0.97**	**1.29**	**2.15**
Draft	**1.07**	**1.21**	**1.42**	**1.11**	**1.03**	**2.20**	**0.82**	**1.14**	**2.00**
Specific Draft kN/cm2	0.010216	0.00515	0.004148886	0.008158178	0.005383929	0.004792174	0.0078066	0.005195712	0.007846

Table 8-7 Draft Data at 3.0m hitching length for Machakos Experimental Site

	Hitching length = 3m								
	Plot 4	Plot 4	Plot 4	Plot 5	Plot 5	Plot 5	Plot 6	Plot 6	Plot 6
	0-10	10_20	20-30	0-10	10_20	20-30	0-10	10_20	20-30
	0.48	1.12	1.48	0.34	0.8	2.16			1.28
	0.54	1.22	1.70	0.42	0.88	2.24	0.60	0.54	1.86
	0.68	1.28	1.78	0.46	0.80	2.36	0.58	0.86	2.40
	0.80	1.16	1.84	0.36	0.72	2.24	0.64	0.70	2.82
	0.86	1.14	1.96	0.32	0.70	2.26	0.58	0.60	2.86
	0.90	1.16	1.96	0.34	0.86	2.46	0.52	0.68	2.76
	0.86	1.32	1.98	0.38	0.96	2.44	0.64		2.74
	1.00	1.20	2.08	0.44	0.86	2.38	0.66	0.86	2.82
	0.94	1.22	2.12	0.36	0.88	2.42	0.58	0.74	2.52
	0.80	1.16	2.16	0.38	0.84	2.50	0.62	0.72	2.86
	0.78	1.12	2.26		0.88	2.52	0.66	0.68	2.78
	0.84	1.20	2.32		0.76	2.34	0.60	0.58	2.58
	0.92	1.12	2.36		0.66	2.04	0.52	0.56	2.70
	0.94	1.06	2.42		0.72	2.10	0.60	0.68	2.58
	1.08	1.08	2.48		0.68	2.38	0.64	0.74	2.54
	0.92	1.10	2.52		0.64		0.60	0.64	2.56
	0.78	1.20	2.72		0.70		0.70	0.62	2.72
	0.82	1.14	2.78		0.66		0.64	0.68	2.62
	0.80	1.18	2.78		0.64		0.62	0.58	2.82
	0.70	1.16	2.84		0.70		0.72	0.64	2.52
	0.78	1.14	2.90		0.72		0.64	0.72	2.16
	0.86	1.16			0.78		0.74	0.68	1.86
	0.58	1.20			0.74		0.68	0.72	1.36
	0.48	1.06			0.70		0.70	0.68	1.22
	0.40	1.18			0.78		0.76	0.64	1.20
	0.38	1.00			0.76		0.84	0.68	1.22
	0.36	1.18			0.68		0.80	0.58	
	0.42	1.00					0.74	0.50	
		1.04					0.78	0.48	
		1.10					0.82	0.56	
		1.06					0.86	0.78	
		1.08					0.90	0.84	
		1.04					0.94	0.60	
		1.08							
		1.06							
		1.08							
		1.16							
		1.02							
Average	**0.74**	**1.13**	**2.26**	**0.38**	**0.76**	**2.32**	**0.69**	**0.66**	**2.32**
Draft	**0.61**	**1.00**	**2.13**	**0.27**	**0.65**	**2.21**	**0.54**	**0.51**	**2.17**
Specific Draft kN/cm2	0.00448	0.005353	0.006591	0.002769	0.003935	0.007024	0.005944	0.003888	0.007514

Table 8-8 Draft Data at 3.5m hitching length for Machakos Experimental Site

	Hitching Length = 3.5m								
	Plot 7	Plot 7	Plot 7	Plot 8	Plot 8	Plot 8	Plot 9	Plot 9	Plot 9
	0-10	10_20	20-30	0-10	10_20	20-30	0-10	10_20	20-30
	1.06	0.94	2.30			1.86		1.2	
	1.30	0.90	2.22	1.12	1.22	1.80	1.00	1.28	
	1.32	1.02	1.38	1.38	1.12	2.30	1.06	1.20	
	1.42	0.88	1.78	1.28	1.18	2.46	1.08	1.26	
	1.36	0.86	2.10	1.20	1.22	2.48	1.04	1.20	
	1.38	0.94	2.14	1.28	1.20	2.68	1.10	1.40	
	1.42	0.98	2.54	1.20	1.08	2.44		1.26	
	1.32	0.90	2.56	1.24	1.16	2.64	1.00	1.24	
	1.26	0.86	2.34	1.26	1.20	2.58	1.04	1.22	
	1.28	0.84	2.20	1.18	1.14	2.40	1.00	1.08	
	1.24	0.92	2.24	1.24	1.12	2.50	0.94	1.16	
	1.20	0.94	2.28	1.26	1.18	2.24	0.88	1.24	
	1.32	0.92	2.20	1.30	1.28	2.04	0.94	1.26	
	1.24	0.88	2.04	1.24	1.14		1.02	1.14	
	1.30	0.90	2.14	1.10	1.22	2.06	0.98	1.16	
	1.36	0.92	1.84	1.04	1.18	2.34	0.92	1.20	
	1.28	1.02	1.60	1.08	1.12	2.04	0.96	1.10	
	1.24	0.90	1.58	1.06	1.10	2.00	0.92	1.06	
	1.22	0.88	1.44	1.08	1.12	2.12	1.08	1.00	
	1.26	0.94	1.94	0.96	1.08	2.18	1.00	1.02	
	1.18	0.82	1.82	0.92	0.98	2.16	0.94	0.92	
	1.16	0.80	1.90	1.00	1.10		0.96	0.96	
	1.06	0.72	2.06	1.08	1.18		0.92	0.90	
	0.92	0.74	2.14	1.06	1.12		0.84	0.92	
	0.98	0.78	2.36	0.80	1.02		0.90	1.02	
	1.10	0.74	2.34		1.00		0.88	0.94	
	1.14	0.72	1.98		1.16		0.94	1.02	
	1.26	0.68	1.26		1.08		1.00	1.06	
	1.28	0.72			1.12		0.96	0.96	
	1.20	0.76			1.16		0.92	1.00	
	1.04	0.84			1.14		0.98	0.94	
	1.02	0.74			1.06		1.00	0.96	
	1.00	0.86			1.04		0.90	1.02	
	1.04	0.78			1.12		1.08	0.98	
		0.70					1.04	0.96	
		0.66					0.96	1.08	
		0.72					0.98	0.90	
		0.52					0.96	0.96	
							0.86	1.24	
Average	**1.21**	**0.83**	**2.03**	**1.14**	**1.13**	**2.27**	**0.97**	**1.09**	
Draft	**1.08**	**0.70**	**1.90**	**1.03**	**1.02**	**2.16**	**0.82**	**0.94**	**(0.15)**
Specific Draft kN/cm2	0.01039	0.005323	0.007021	0.012262	0.008107	0.011056	0.007343	0.007104	**(0.0007)**

Table 8-9 Draft Data at 2.5m hitching length for Kitui Experimental Site

	Hitching length = 2.5m								
	Plot 1	**Plot 1**	**Plot 1**	**Plot 2**	**Plot 2**	**Plot 2**	**Plot 3**	**Plot 3**	**Plot 3**
	0-10	**10_20**	**20-30**	**0-10**	**10_20**	**20-30**	**0-10**	**10_20**	**20-30**
	1.54	1.10	1.66	0.52	1.96	1.98	1.96	1.30	1.86
	1.36	1.76	2.10	1.22	1.38	1.86	1.08	1.08	1.94
	1.40	1.68	2.14	1.08	1.22	1.80	1.48	1.20	2.42
	1.32	1.40	1.50	1.38	0.96	2.04	1.42	1.18	2.16
	1.74	1.30	1.94	1.36	1.06	2.10	0.78	1.36	2.80
	1.48	1.32	2.40	1.52	1.18	2.42	1.90	1.84	2.86
	2.00	1.58	2.58	1.58	1.36	1.80	1.34	1.62	2.52
	1.98	1.68	2.72	1.26	1.64	2.02	1.88	1.74	2.35
	1.68	1.74	1.82	1.46	1.54	2.04	0.82	1.42	2.76
	1.44	2.18	1.86	1.30	1.28	1.82		1.12	1.14
	1.72	1.60	1.90	1.06	1.20	1.72		1.46	2.38
		1.44	1.72		1.36	2.00		1.74	2.22
		1.78	1.44		1.76	2.48		1.70	3.08
		1.18	1.32		1.82	1.80		1.48	1.98
		1.48	1.38		1.74	2.02		1.92	1.86
		1.62	1.86		1.22	1.92		1.26	
		2.08	1.90		1.28	1.76		1.08	
		1.68	1.72		1.44	1.62		1.28	
		1.54	1.44		1.48	2.08		1.32	
			1.38		1.26	2.18		1.30	
			2.20		0.88			1.40	
			2.52		1.30			0.98	
			2.30		1.72				
			2.50						
			2.14						
Average-Dav	1.61	1.59	1.94	1.25	1.39	1.97	1.41	1.40	2.29
Actual Draft	1.28	1.27	1.62	0.62	0.76	1.34	(0.03)	(0.04)	0.85
Specific Draft	0.008	0.007	0.006	0.005	0.003	0.006	(0.0004)	(0.0001)	0.0022

Table 8-10 Draft Data at 3.0m hitching length for Kitui Experimental Site

	Hitching length = 3m								
	Plot 4	Plot 4	Plot 4	Plot 5	Plot 5	Plot 5	Plot 6	Plot 6	Plot 6
	0-10	10_20	20-30	0-10	10_20	20-30	0-10	10_20	20-30
	0.86	1.02	2.38	1.42	1.46	0.74	1.04	0.82	1.12
	1.36	1.32	1.54	1.50	1.58	1.70	1.22	1.42	1.24
	1.12	1.60	1.84	1.60	1.74	1.80	1.36	1.94	1.48
	1.36	1.68	2.06	1.48	2.10	1.82	1.50	1.98	1.56
	1.18	1.56	2.79	1.68	1.68	2.60	1.46	1.64	1.76
	1.58	1.36	1.68	1.54	2.16	1.02	1.28	1.40	1.48
	1.40	1.66	2.74	1.52	1.86	1.28	1.40	2.06	1.76
	1.44	1.74	2.10	1.46	1.94	1.06	1.16	2.44	2.10
	1.78	1.42		1.60	1.98	1.16	1.58	2.32	2.22
	1.50	1.64		1.62	1.78	2.16	1.52	1.46	2.08
	1.12	1.62		1.64	1.54	2.20	1.74	1.76	1.54
	1.46	1.70		1.58	1.64	2.42	1.34	2.14	1.48
	1.54	1.90		1.48	2.14	2.62	1.30	1.64	1.06
	1.38	1.50		1.28	2.20	2.86	1.40	2.60	1.30
	1.84	1.52		1.54	2.22	2.48	1.36	1.68	1.92
	1.70	1.44		1.40	1.42	2.26	1.26	1.46	2.28
	1.94	1.28		1.46	1.94	3.48	1.30	1.28	3.10
		1.44			1.70	2.16	1.58	1.86	2.42
					1.92	2.44	1.56	1.74	1.16
					1.72		1.46	1.70	1.22
					1.82		1.20		1.50
					1.42		1.36		1.80
					1.62		1.10		2.20
					1.30		1.12		2.02
							1.30		
							1.28		
							1.24		
Average-Dav	1.44	1.52	2.14	1.52	1.79	2.01	1.35	1.77	1.74
Actual Draft	1.12	1.20	1.82	0.89	1.16	1.38	- 0.09	0.33	0.30
Specific Draft	0.0075	0.0057	0.0057	0.0066	0.0034	0.0037	(0.00057)	0.00108	0.00134

Table 8-11 Draft Data at 3.5m hitching length for Kitui Experimental Site

	Hitching Length = 3.5m								
	Plot 7	Plot 7	Plot 7	Plot 8	Plot 8	Plot 8	Plot 9	Plot 9	Plot 9
	0-10	10_20	20-30	0-10	10_20	20-30	0-10	10_20	20-30
	1.40	1.48	1.38	1.36	1.36	0.92	1.66	1.66	2.12
	1.98	1.20	1.42	1.40	2.00	0.52	1.80	1.68	2.06
	2.62	1.38	1.62	1.00	1.84	0.58	1.42	1.90	2.04
	2.24	1.22	1.86	1.28	1.96	1.16	1.54	2.00	1.82
	2.86	1.12	2.00	1.36	1.56	1.80	1.48	2.04	1.70
	3.82	1.34	2.20	1.24	1.48	1.88	1.78	1.76	2.04
	2.75	1.50	1.86	1.46	1.96	1.56	1.80	1.58	2.54
	2.40	1.16	1.40	1.74	2.20	1.66	1.70	1.56	1.88
	1.92	1.68		1.44	2.18	1.78	1.52	1.70	1.30
	1.96	1.16		1.08	1.54	2.22	1.60	1.94	1.10
	1.54	1.12		1.32	1.56	1.86	1.78	1.76	1.04
	2.86	1.50		1.60	1.82	0.90	1.66	1.78	0.94
	1.48	1.68		1.56	1.64	0.44	1.38	1.88	1.40
	1.22	1.26		1.64	2.06	0.52		1.80	1.74
	1.64	1.04		1.46	2.00	0.38		1.58	2.00
				1.44	1.96	0.60		1.60	1.78
					1.28	1.04		1.56	1.72
					0.96	2.10		1.42	1.78
					1.46	1.06		1.34	1.66
					1.60	0.54		1.36	1.58
					0.92	0.38		1.26	1.50
					1.62	0.44			1.40
					1.32				1.74
					1.18				1.84
					1.88				2.02
					1.62				2.44
					2.12				1.94
					1.50				1.88
					1.90				2.16
					1.18				2.44
									2.74
									2.76
									2.66
									1.50
									1.20
									1.30
									1.14
									1.32
Average-Dav	2.18	1.32	1.72	1.40	1.66	1.11	1.62	1.67	1.80
Actual Draft	1.86	1.00	1.40	0.77	1.03	0.48	0.18	0.23	0.36
Specific Draft	0.0130	0.0033	0.0119	0.0038	0.0032	0.0019			

Appendix E: Penetration Resistance Data

	Plot 1						Plot 2						Plot 3					
	0-10		10_20		20-30		0-10		10_20		20-30		0-10		10_20		20-30	
	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui
	56.4	58.8	46.8	48	43.2	58.8	58.8	57.6	50.4	60	48.6	60	58.2	57.6	57.6	59.4	59.4	57.6
	58.8	58.2	55.8	53.4	46.2	57	59.4	59.4	53.4	58.2	59.4	60	60.0	60	60.0	45	50.4	59.4
	57.6	55.2	55.8	55.2	50.4	59.4	58.8	60	57.0	60	59.4	60	58.8	54.6	57.0	58.2	60.0	59.4
	48.0	49.2	60.0	58.8	51.0	57.6	59.4	60	58.2	59.4	59.4	58.8	60.0	60	59.4	59.4	59.4	60
	51.0	54	55.2	60	45.0	58.8	55.2	59.4	57.0	60	60.0	49.2	58.2	57.6	58.8	58.2	54.6	59.4
	51.6	51.6	60.0	59.4	50.4	58.8	60.0	59.4	58.8	59.4	60.0	59.4	60.0	50.4	60.0	60	59.4	59.4
								59.4		60		59.4		51		60		60
																		58.8
Average Resistance	**53.9**	**54.5**	**55.6**	**55.8**	**47.7**	**58.4**	**58.6**	**59.3**	**55.8**	**59.6**	**57.8**	**58.1**	**59.2**	**55.9**	**58.8**	**57.2**	**57.2**	**59.3**

	Plot 4						Plot 5						Plot 6					
	0-10		10_20		20-30		0-10		10_20		20-30		0-10		10_20		20-30	
	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui
	48.0	52.2	40.20	55.8	54.60	58.8	51.0	58.8	51	57.6	59.4	60	56.4	56.4	37.8	60	57.6	57.6
	60.0	55.2	52.20	60	49.80	60	60.0	53.4	55.2	58.8	60	59.4	57	57.6	43.2	60	57.6	60
	60.0	57	45.60	57.6	58.80	58.8	56.4	52.2	58.8	55.2	56.4	59.4	60	60	55.2	59.4	56.4	58.2
	53.4	51	46.20	59.4	59.40	59.4	60.0	38.4	54.6	58.2	57.6	60	58.8	60	57	55.8	45	58.2
	57.0	58.8	52.20	58.8	57.60	58.8	56.4	45.6	58.8	56.4	60	60	60	60	47.4	59.4	54.6	60
		55.8	55.20	58.2	58.80	59.4	60.0	46.8	58.2	55.8	55.8	60	59.4	55.8	48	59.4	54.6	59.4
		60		55.2		60	-	48		60	57	59.4	59.4	59.4	45	58.8	51.6	60
														55.2		59.4		59.4
Average Resistance	**55.7**	**55.7**	**48.6**	**57.9**	**56.5**	**59.3**	**49.1**	**49.0**	**56.1**	**57.4**	**58.0**	**59.7**	**58.7**	**58.1**	**47.7**	**59.0**	**53.9**	**59.1**

	Plot 7						Plot 8						Plot 9					
	0-10		10_20		20-30		0-10		10_20		20-30		0-10		10_20		20-30	
	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui	Machakos	Kitui
	48.6	55.8	44.4	56.4	58.8	43.2	48	44.4	42.6	60	56.4	54	39.0	42	50.4	60	58.8	54
	45.0	51.6	51.6	59.4	58.8	43.8	60	49.2	45.6	59.4	49.8	56.4	51.0	43.2	55.2	59.4	51	59.4
	54.6	52.2	55.8	60	58.8	43.8	59.4	58.8	48.6	60	48	60	58.2	54.6	57.6	60	58.2	58.8
	60.0	57.6	58.2	59.4	57.6	52.8	58.8	57	51	60	45.6	59.4	51.6	56.4	48	56.4	58.2	57.6
	55.2	59.4	58.8	58.8	55.8	57.6	58.8	50.4	58.8	60	47.4	58.8	43.8	58.2	46.8	54	58.8	57
	58.2	55.8	59.4	60	54.6	55.2	55.2	51	57.6	59.4	52.2	59.4	52.8	54.6	46.2	58.2	57.6	60
	60.0	59.4	57	58.8	58.2	59.4	58.8		58.2		48.6		52.2		54.6		57.6	
					58.2				58.8		51.6		48.6		51.6		58.8	
Average Resistance	**54.5**	**56.0**	**55.0**	**59.0**	**57.6**	**50.8**	**57.0**	**51.8**	**52.7**	**59.8**	**50.0**	**58.0**	**49.7**	**51.5**	**51.3**	**58.0**	**57.4**	**57.8**

Appendix F: Texture Analysis (Mechanical Analysis)

Method 1: Limited pretreatment of the soil; hydrometer readings.

Apparatus and other requirements:

Bouyoucos hydrometers or ASTM hydrometers No 152H.

Sedimentation cylinders, marked at 1000ml and length bottom to mark = 34 – 38cm

Special plunger or rubber stopper, that fits on the sedimentation cylinders, for mixing.

Conical flask, 1000ml.

Stopwatch or an accurate clock with seconds hand.

Thermometer with room temperature range.

Balance, accurate up to 0.01g

End-over-end mechanical shaker

500ml plastic bottles with screw cap.

Reagents: approx. 0.5 N Na:

Calgon solution; approx. 0.5N Na:

Dissolve 40.0g pre-of dried, powdered sodium hexametaphosphate (mainly $(Na\ PO_3)_6$) in 750ml. DW in a 1000ml conical flask, by slowly adding it to the water while stirring. Then add 10g of pre-dried anhydrous sodium carbonate (Na_2CO_3) and make up to 1litre with DW.

Deionised or distilled water(=DW).

Procedure:

Weigh 50.0g of soil in 500ml plastic shaking bottles, add 50ml of Calgon solution and leave overnight. Add about 400ml DW, tightly stopper the bottles and shake in an end-over-end shaker during 10minutes. Include a blank (No soil but with all other addition)

Transfer the soil suspension to the 1000ml sedimentation cylinders, rinse the plastic bottles well with DW make up to the mark with DW. Stir the suspension well with the plunger, or after the placement of the rubber stopper by hand shaking. Stop shaking when the seconds hand indicates 60seconds. Place the cylinder carefully on the table. Slowly immerse the hydrometer in the suspension and take a hydrometer – and a temperature reading of the suspension when the seconds hand indicates (for the first time) 40 seconds. Record the readings. Out of these readings the silt + clay content of the sample can be calculated.

Leave the cylinder, without touching, on the table.

Repeat the same readings (temperature and hydrometer) after 6-5 hours.

Out of these readings the clay content can be calculated.

Calculation

The hydrometer is calculated at 20° c. For this reason, a correction has to be made when the temperature is higher or lower.

$$\%Sand = \frac{100 - ((R1 - B1) + 0.36(T1 - 20) * 100}{W}$$

For 50g of soil: $\%Sand = 100 - 2((R1 - B1) + 0.36(T1 - 20))$

$$\%Clay = \frac{((R2 - B2) + 0.36(T2 - 20) * 100}{W}$$

For 50g of soil: $\%Clay = 2((R2 - B2) + 0.36(T2 - 20))$

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

Where:

R1= first reading hydrometer sample.

B1 = first reading hydrometer blank.

R2= Second reading hydrometer sample

B2 = sec. reading hydrometer blank

T1= first temperature reading

T2= second temperature reading

0.36= temperature correction factor (in °C)

20= hydrometer calibration temperature (in °C)

W= weight of sample taken for analysis (50g or 51g)

Note:

Temperature differences between inside and outside the sedimentation cylinder causes turbulence in the cylinder. This will give errors. To overcome this, the cylinders should be left in a water bath of which the water has the same temperature as that in the cylinders or the whole analysis should be performed in a room with a constant temperature

Appendix G Experimental Sites

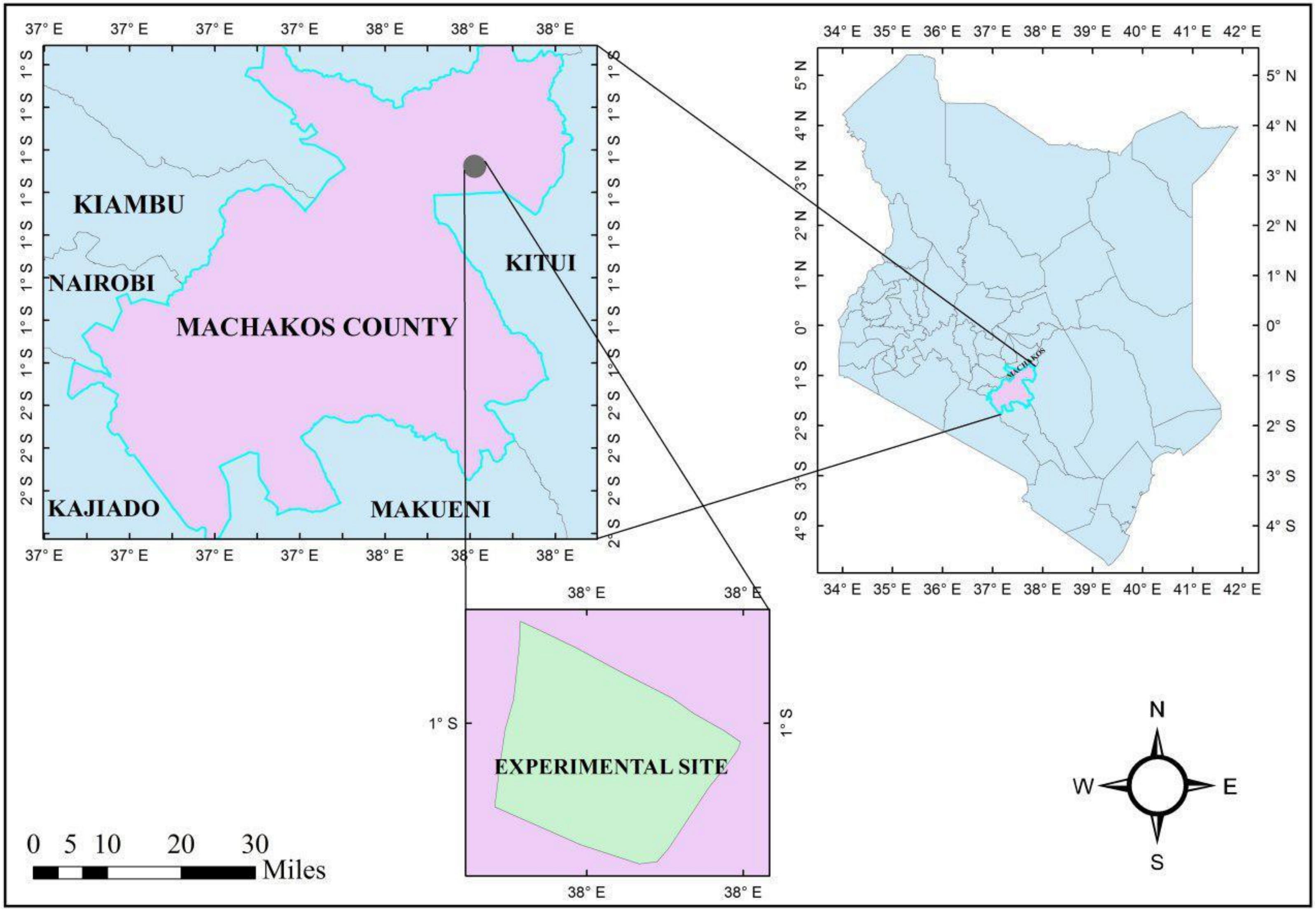

Figure 8-15: Machakos Experimental Site

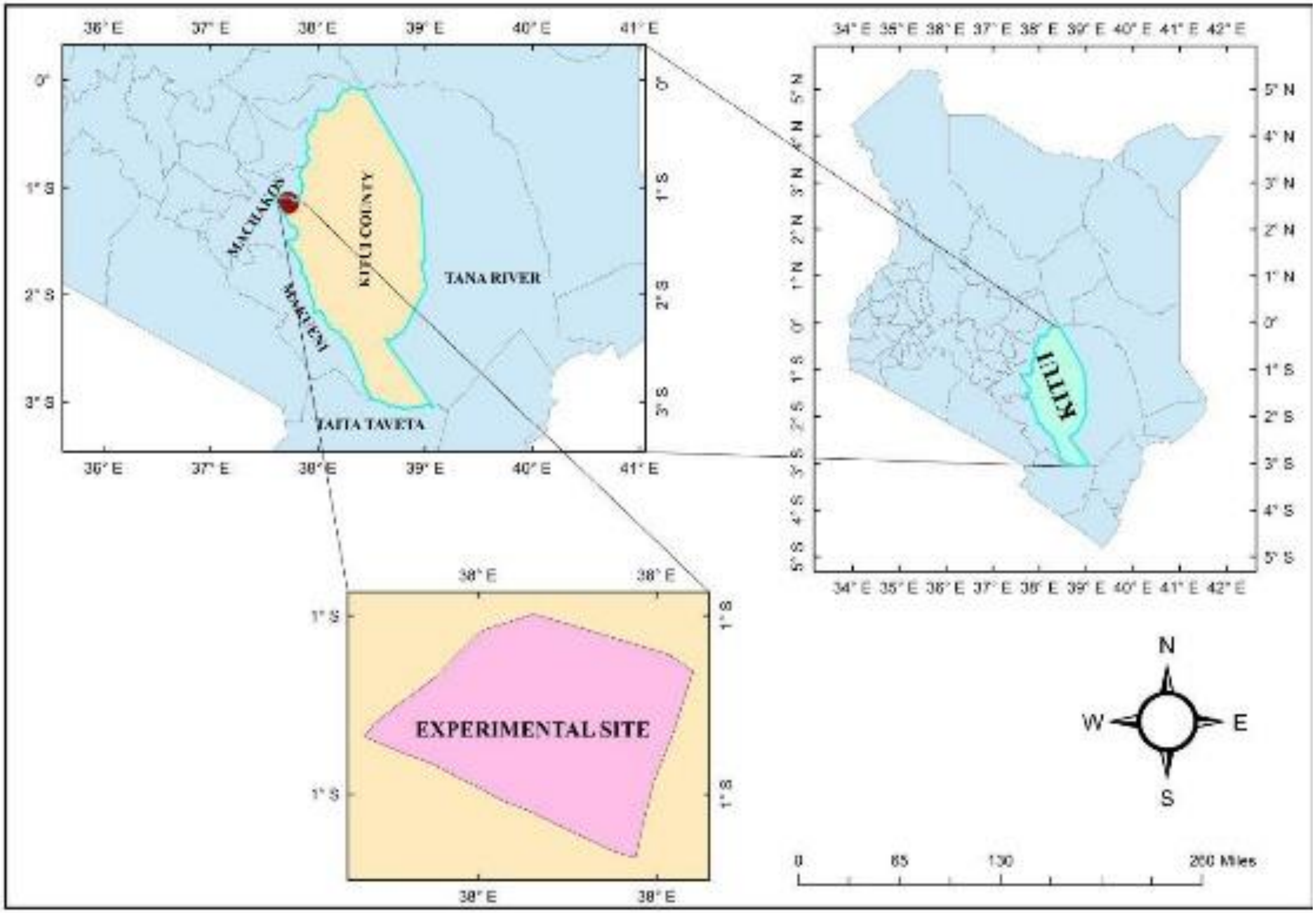

Figure 8-16 Kitui Experimental Site

Appendix H: Subsoiler Specifications

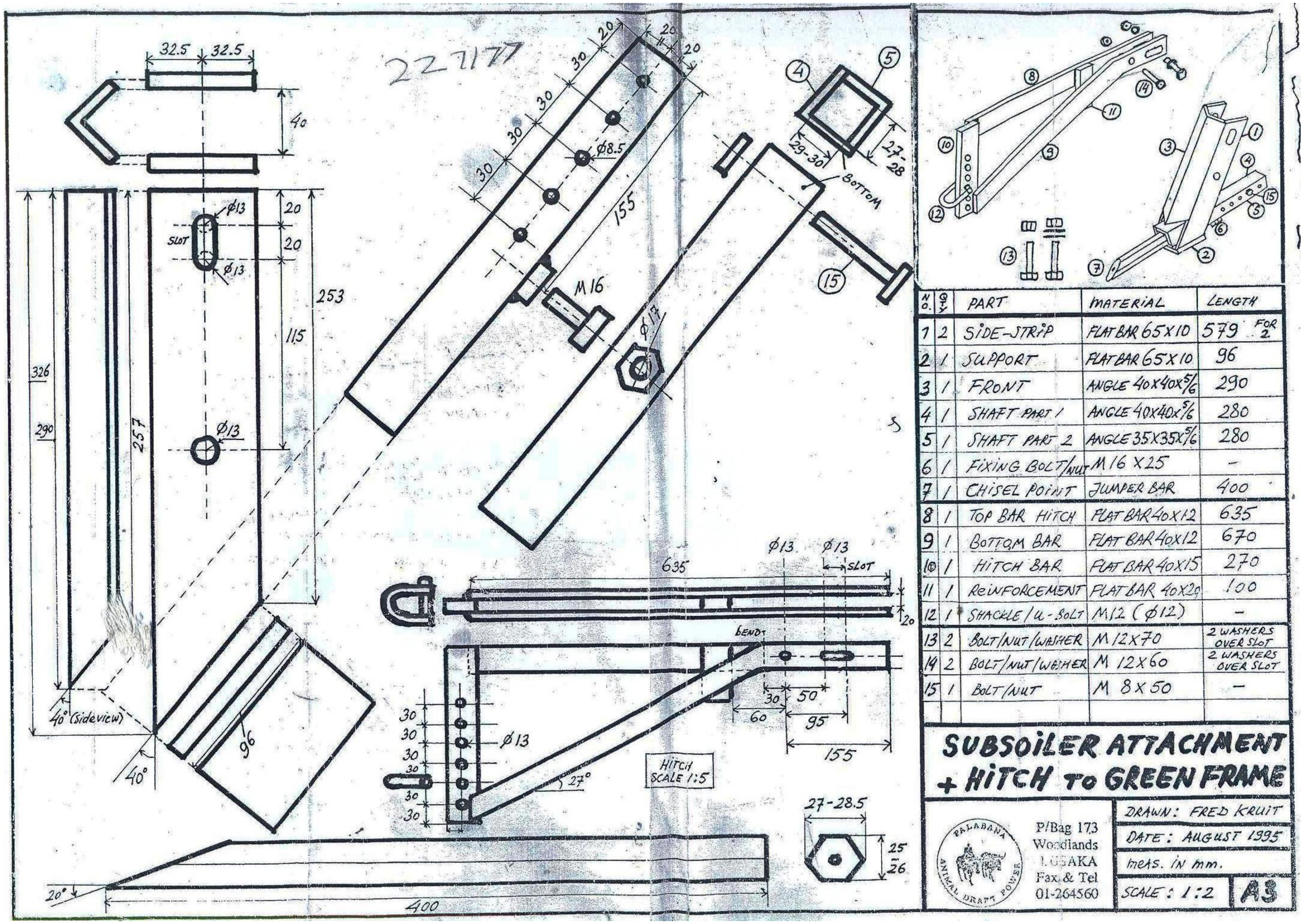

Figure 8-17 Subsoiler Specifications

Appendix I: Terminologies

Angle of internal friction: Soil friction angle is a shear strength parameter of soils. Its definition is derived from the Mohr-Coulomb failure criterion and it is used to describe the friction shear resistance of soils together with the normal effective stress. In the stress plane of Shear stress-effective normal stress, the soil friction angle is the angle of inclination with respect to the horizontal axis of the Mohr-Coulomb shear resistance line.

Conservation tillage: Any tillage or seeding system that maintains a minimum of 30% residue cover on the soil surface after planting to reduce soil erosion by water during the critical erosion period.

Critical depth: A depth that depends on the slenderness of a tillage tool below which soil compaction other than loosening occurs.

Draft: This is the pull required to operate an agricultural tool or generated by a prime mover to pull an agricultural tool.

Dynamometer: A force measuring device that operates in both the horizontal and vertical axes without taking lateral forces.

Gravimetric Analysis: Analysis based on mass/ weight measurements.

Hitch: The portion of an implement designed to connect the implement to a power source

Iteration: Is the act of repeating a process with the aim of approaching a desired goal, target or result.

Mechanized agriculture is the process of using agricultural machinery to mechanize the work of agriculture, greatly increasing farm worker productivity.

Mohr coulomb theory: This theory states that material fails because of a critical combination of normal shear stress and not from either maximum stress or shear stress alone.

Poisson's Ratio: Is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force.

Prototype: an early sample, model, or release of a product built to test a concept or process or to act as a thing to be replicated or learned from.

Shear Modulus: Is the ratio of shear stress to the shear strain.

Soil-cut Interaction: This is defined as the process in which the response of the soil influences the motion of the tool and tool influences the response of the soil.

Specific draft (unit draft): Draft force of an implement per unit area of tilled cross section.

Subsoiler A chisel-shaped agricultural implement that can be animal or tractor powered. It breaks up and opens a narrow slot or furrow in the soil to loosen and aerate the soil while leaving crop residue at the top of the soil without overturning the soil.

Sub-soiling: Deep tillage, below 350 mm for the purpose of loosening soil for root growth and/or water movement

Tillage: This is the preparation of soil for agricultural purposes by mechanical agitation of various types, such as digging, stirring, and overturning.

Tine: A 'prong' on an agricultural tool or similar implement characterized by an end that is more or less sharp or pointed.

Young's modulus: Is the ratio of the stress (force per unit area) along an axis to the strain (ratio of deformation over initial length) along that axis in the range of stress in which Hooke's law holds