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DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

RAKE ANGLE EFFECT ON DRAFT POWER REQUIREMENT: CASE OF A SUB-SOILER IN NITISOLS

BY

KENNEDY WANDERA MAKUDIUH, (F56/64020/2010)

B.Sc Agric. Eng. (1993)

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Name of student: **KENNEDY WANDERA MAKUDIUH.**

Registration: **F56/64020/2010.**

College: **ARCHITECTURE AND ENGINEERING.**

Faculty/School/Institute: **SCHOOL OF ENGINEERING.**

Department: **ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING.**

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DEDICATION

I dedicate this work to my beloved wife Marian Ojiambo Wandera, children Winnie Sidonge, Larisa Nangira, Merceline Nabwire and George Makudiuh for their emotional support, words of encouragement and tolerance for my almost absence during this time. I could not attend to your needs effectively but your understanding has brought me this far.

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ACRONYMS

ASAL	Arid and Semi- Arid Lands
AVONA	Analysis of Variance
CA	Conservation Agriculture
CI	Cone Index
cm	Centimeters
cm^2	Centimeter squared
cm^3	Centimeter cubed
CT	Conservation Tillage
FAO	Food and Agriculture Organization of the United Nations
gms	Grams
PSD	Particle Size Distribution
SED	Standard Error of Distribution
SSA	Sub - Sahara Africa
CTIC	Conservation Technology Information Center

ABSTRACT

Draft animals are key to the provision of draft power for tillage in small-holder farms that have limited access to tractors. There is limited information on guidelines for utilization of animal draft, particularly for sub-soiling which is a more recent conservation tillage technology. The limited information on draft requirement for sub-soiling that demands large amounts of draft has resulted in sub-soiling tools that are poorly adapted to local conditions and are neither economical nor environmentally sustainable. Further studies are required to address insufficient on-farm draft for sub-soiling by correctly matching the prime mover with the relevant implement 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. A study was initiated at University of Nairobi, College of Agriculture and Veterinary Sciences, Kabete Campus whose broad objective was to evaluate the effect of varying the rake angle on the draft power requirement for a sub-soiler in Nitisols. The specific objectives were to: Identify the soil physical characteristics at the experimental field pertinent to sub-soiling, Assess the effect of rake angle, speed and depth of tillage on specific draft force tillage, Establish prediction model for specific draft force based on rake angle, speed and depth of tillage and Identify rake angle, depth and speed for optimization of specific draft force. An experimental plot of 50m long by 5m wide was used. A block of 30m long by 5m wide was used as a pilot area prior to the beginning of the experimental runs to enable the tractor and the implement attain the required speed and depth. Two tractors were used in this study. The first tractor towed the second tractor with a dynamometer attached between to measure draft. The Sub-soiler was hitched on the second tractor. Readings from the dynamometer were taken at pre-determined intervals. The parameters investigated for the draft measurement were forward speed and depth of sub-soiling. For the five rake angles, two forward speeds and three depths were used in combination for 30 treatments. Tillage depth was measured as the vertical distance from the top of the undisturbed soil surface to the implements deepest penetration point. Effects of rake angle on draft power were assessed by ANOVA using the linear mixed model in Genstat Statistical Package. Regression was used to fit a model to predict draft force from tillage depth, speed and rake angle. The difference in draft power between tillage speeds was not significant (P=0.088). Rake angle and tillage depth had significant main (P<0.001) and interactive effects on draft power requirement (P=0.023). For small rake angles ($<40^0$), the draft power increased linearly with sub-soiling depth while at greater rake angles ($>40^o$) the relationship was also linear but skewed to the left. The least square fit for second order relationship coefficient between rake angles and draft force at the 300 mm was 0.956 and significant (P<0.05) allowing prediction of the draft requirement for the sub-soiler on clay soils. In conclusion, the critical tillage depth for sub-soiling on clay soils is at least 300 mm. Sub-soilers in Kenya are currently produced with a general rake angle of 50^o for all types but for clay soils, there is need to increase the rake angle to 72^o for optimal sub-soiling. Further studies should focus on assessing the effect of sub-soiler rake angle on power requirement in Nitisols at tractor ploughing speeds and multi-locational studies for other soil types such as Ferralsols which are prone to compactions.

Keywords: Subsoiler's Rake Angle, Critical Depth, Draft Power Requirement, Sub-soiling, Nitisols

1.0 INTRODUCTION

1.1 STUDY BACKGROUND

The design of tillage tools to accomplish different jobs is a very complex engineering work (Shmulevich, 2010). This is based on the fact that different crops require different soil preparations (Dardanelli *et al.*, 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).

Tillage tools of different shapes and sizes have been designed and constructed for the purpose of soil manipulation (Inns, 1990). One of the most important performance criteria in tillage tool design is the force needed to pull the tool through a given soil (Godwin, 2007). Cumulative effects of heavy field equipment have become more apparent in the past decade with increased frequency of soil compaction problems (Batey, 2009). Subsoiler's of different designs have been developed and used in attempts to reduce compaction (Raper, 2007 and Reeder and Wood, 1993) . Whatever the benefits may be, subsoiling is a high energy tillage operation and should be done only after carefully considering all management options (Ghosh *et al.*, 2006).

Draft and power requirements are important parameters for measuring and evaluating performance of tillage implements and therefore are considered as essential data when attempting to correctly match tillage implement to a prime-mover (Sahu and Raheman, 2008). Many studies have been conducted to measure draft and power requirements of tillage implements under various soil conditions. Implement width, operating depth and speed are factors that affect draft of a tillage implement (Al-Suhaibani, 2010). Draft also depends on soil conditions and geometry of the tillage implements (Tong and Moayad, 2006). The effect of speed on implement draft depends on the soil type and the type of implement (Al-Suhaibani, 2010). It has been widely reported that the draft forces on implements increase significantly with speed and the relationship varies from linear to quadratic (Collins and Fowler, 1996).

Smallholder farm mechanization in sub-Saharan Africa (SSA) relies heavily on manual labor and the hand hoe is the main implement used for crop production on up to 80% of the arable land area. Draught animal power (DAP) represents a major advance in terms of available power and is especially important where human resources are being depleted by age, migration, and pandemics. However the use of DAP is restricted by the presence of the tsetse fly and by tick-borne diseases such as east-coast fever (FAO, 2006). 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). Of these three factors, a designer has complete control only over the geometry of the tool, as initial soil condition changes from place to place 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 declining availability of draft animal power, it is imperative to evaluate the performance of an animal drawn Subsoiler at different cutting angles under established soil.

Godwin (2007), studied the effect of Subsoiler speed on forces and soil disturbance in clay loam and compact loam soils. The tool speed had highly significant linear effects on the vertical force and highly significant quadratic effects on the horizontal force, total force, moment and specific resistance.

The effect of force on furrow openers having different rake angles was studied by Günay *et al.* (2005). The convention used to represent rake angle varied, however if rake angle is dented by the angle which the furrow opener makes with the horizontal in the direction of travel, then the general conclusion was that both horizontal and vertical forces increase with increased rake angles as stated by Günay et al. (2005). Tong and Moayad (2006) concluded analytically as well as from experimental results that a rake angle of 15^0 gave the lowest draft for a chisel plough. For light sandy soils, a rake angle of 130° was found to be best for the depth stability of the furrow openers (Chaudhuri, 2001).

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 Calcic Chernozem and Haplic Kastanozem 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). Onwualu and Watts (1998) in a study on the relationship between tillage tool forces and speed which is important in evolving management strategies for optimum performance found the tool force (draught and vertical force) to be a function of the speed and the square of speed. Mouazen and Nemenyi (1999) showed that a well-coordinated angle combination of the two parts of the Subsoiler made a large reduction in the draught and vertical forces of the Subsoiler with a shank angle of 75° and a chisel angle of 15°. Godwin and O'Dogherty (2007) in a review on the integration of a series of models to predict the forces acting on a range of tillage tools from simple plane tines to mouldboard ploughs showed that horizontal (or draught) and vertical forces can be predicted with average errors of −3% and +33%, with the majority of the predicted values within ±20% and ±50% of the measured values respectively. Further, the models adequately reflect the changes in soil strength and implement geometry and all of the predicted values given have been estimated using a spreadsheet based model which is freely available. Studies on the effect of varying rake angle on draft power requirement of a Subsoiler on Nitisols, particularly in the central Kenya Highlands are limited hence the need for this study.

1.2 PROBLEM STATEMENT

Currently, there is no general consensus on the use of animal draft power for land preparation. On one hand, some opine that efficient and timely land preparation can be realized only through the use of mechanization by tractors (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 (Mrema and Mrema, 1993). Such opinions serve mainly to confound a simple and general solution to a very complex problem as neither tractorisation nor animal traction can be singly employed under all farming conditions. Failure to implement land preparation strategies which integrate both tractor and animal traction will continue to result in inefficient use of resources for land preparation, especially for conservation tillage in small-scale farms of sub-Saharan Africa where capital resources are limited (Temesgen *et al.*, 2009). 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 75% of the agricultural power (Gitau *et al.*, 2012). Animals utilized as a source of traction, include horses, mules, asses, buffalo and cattle. In addition to furnishing a source of power, these same animals provide milk, 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. The limited research on draft requirement for sub-soiling that demands large amounts of draft has resulted in sub-soiling tools that are poorly adapted to local conditions and are neither economical nor environmentally sustainable. The only animal drawn sub-soiler on the market is fabricated at a fixed rake angle of 50^0. This sub-soiler is expected to operate in all types of soils regardless of their physical and mechanical characteristics. It is the draft animals which end up suffering in this case.Further studies are required to address insufficient on-farm draft by optimizing on the limited animal draft power by correctly matching the prime mover with the relevant implement based on accurate prediction of draft power requirement. Determination of the rake angle that will require minimum draft power for subsoiling is important. This may result in reduced time for the operation, less draft power requirement, reduced wear/tear and significant savings on costs.

1.3 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). However, it is becoming more apparent that the ploughing techniques developed in temperate regions, which have gentle rains and low wind and water erosion, can have serious adverse effects on the long term productivity of erosion-prone tropical soils. Conservation Agriculture offers a window of opportunity to convert degraded soils into productive soils and thereby improves crop yields, reduces land degradation and generally speaking, addresses environmental conservation concerns (Rusinamhodzi *et al*., 2011 and Giller *et al.*, 2009) .

The availability of draft requirement data of tillage implements is an important factor in selecting suitable tillage implements for a particular farming situation (Johansen *et al*., 2012). Farmers mostly depend on past experience for selecting tractor and implements for various farming operations (Temesgen *et al.*, 2009). This previous experience may be of little effect in selecting newly available implements. Therefore, predictions of implement draft requirement are important for tractor selection and implement matching (Sahu and Raheman, 2008).

Draft and time requirements usually dictate the size of power units required on a given farm (Snijders, 2005). Since the power unit represents a major capital investment, knowledge of draft requirements is necessary in making machinery management decisions. Draft requirements are also needed for decisions that will be used in future energy management of agricultural machinery (American Society of Agricultural and Biological Engineers, 2011). Optimum use of energy is an important design criterion for any agricultural machine.

Quantitative evaluation of tillage implement 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, quantitative descriptions of implement performance are difficult because no standard methods exist for adequately describing soil conditions.

1.4 OBJECTIVE

The broad objective was to evaluate the effect of varying rake angle on the draft power requirement for a sub-soiler in Nitisols.

1.4.1 Specific Objectives

1. To identify the soil physical parameters pertinent to sub-soiling.
2. To assess the effect of rake angle, speed and depth of tillage on specific draft force sub-soiling.
3. To establish prediction model for specific draft force based on rake angle, speed and depth of sub-soiling.
4. To identify rake angle, depth and speed for optimization of specific draft force.

1.5 SCOPE

The effect of varying rake angle on the performance (power/energy requirement) for an animal drawn sub-soiler was tested in the medium rainfall area of Nairobi County (University of Nairobi, College of Agriculture and Veterinary Services). The sub-soiler rake angle was varied from 30^0 to 70^0 in Nitisols

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

In most Sub-Saharan African countries, animal traction for tillage and wheeled transport was introduced during the colonial period (Pingali *et al.*, 1987). The process of introduction and adaptation is still continuing. During the first half of the twentieth century, the colonial authorities or agricultural production companies in several parts of Sub-Saharan Africa, attempted to introduce animal traction for cultivation (Munzinger, 1982). The aim was to increase agricultural production in the colonies by teaching the indigenous population how to use work animals for plowing (Pingali *et al.*, 1987). One of the early schemes took place in 1900 in the West African country of Togo, then under German control (Betker and Kutzbach, 1989). In the hopes of increasing cotton production, a team of black American experts from Alabama were hired by the Berlin Colonial Economic Committee to introduce animal power for cultivation. Further attempts were made in Togo in 1908 (at Mango) and 1913 (at Tabligbo). Although the idea of animal traction was not totally rejected, there was little adoption in Togo at that time. Even with further attempts at introduction in the 1950s, there were probably fewer than 1000 plows in use at the time of independence in 1960 (Asota, 1996).

In 1903, European farmers and traders started to settle in the Machakos District of Kenya. They used heavy plows that required teams of six animals (Thomas *et al.*, 1997). There was no formal promotion of animal traction, but plows were available from trading stores. Some local Kamba farmers apparently started using ox plows in 1910. By 1912, the District Commissioner had noted an increase in farm size and cash-crop production associated with the innovation. By 1933, there were 600 plows in use. The lighter Ransome Victory plow became available in the 1940s, and became the most popular implement. By the late 1950s, almost all farmers in the District were making use of animal power, through ownership or hire (Huho *et al.*, 2009). This high rate of adoption had taken place as a result of private-sector sources of equipment and without any formal extension or credit programmes.

In eastern and southern Africa, immediate post-colonial promotion of animal traction during the 1960s and 1970s involved mainly national Ministry of Agriculture extension services. At this time, while national agricultural engineering services were placing emphasis on the development of tractor hire services, some centres were established to develop new 'appropriate technology' implements and carts (Starkey, 1986). Some centres were established by national Ministries, while others were developed by non-governmental organizations: few worked closely with the end-users and few produced implements that were adopted by farmers. By the 1980s, national 'top-down' extension programmes and services appeared to have limited impact, and there was increased emphasis on area-specific, donor-assisted development projects (Starkey, 1992). Some integrated projects had specific animal traction components, some of which proved highly effective (Mrema and Mrema, 1993). By the 1990s, there was increasing emphasis on participatory and farming systems approaches and linking projects that were working on animal traction (networking).

At the turn of the century, investment in agriculture by donors and national governments in sub-Saharan Africa has halved, while the number of people in need of food aid has doubled (Starkey, 1994 and Biamah, *et al.*, 2000). With the most severe and intractable poverty in the world being in Sub- Saharan Africa (SSA), nearly half of the people live in absolute poverty subsisting on incomes of less than a dollar a day. On present trends, two of the fundamental Millennium Development Goals set by the United Nations, halving the number of people living in absolute poverty and halving the proportion of people suffering from hunger will not be met in SSA by the target year of 2015. In these areas, tackling poverty means boosting smallholder agriculture and recognising that this is the best way of driving broad-based economic growth and poverty reduction (Maurice, 2013).

2.1.1 Alternative power sources

Statistics show that human power still predominates over much of the developing world, contributing over 70% of power requirements (Mazvimavi and Twomlow, 2009). At the same time draft animals contribute nearly a quarter of power needs and tractors only 6%

Table 2.1: Proportional contribution to total power use in selected regions-(%)

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

Certainly in SSA, most rural households are dependent on human or animal power for their tillage operations. Hand tillage is hard, back-breaking work providing very low returns to labour.

Not surprisingly it remains unpopular and a major reason why younger people do not want to work agriculture. At the same time most hand tillage, especially weeding, is often undertaken by women. Unfortunately HIV/Aids is further reducing labour productivity with sick people being unable to undertake hard physical work and able-bodied adults, often women, caring for those infected (Maurice, 2013). Two important questions need to be addressed, "*Can energy use/power requirements be reduced to ensure higher productivity for agriculture, and can the poorest benefit?*"

Although there may be great demand for increased availability and use of tractors, the realities of capital availability, productivity and infrastructure requirements have made mechanisation problematical, especially for the small scale farm sector. For this reason draft animals are likely to remain widely used in transport and for tillage for many years. Surveys, in Zimbabwe for instance (Biamah *et al.*, 2000), have shown that the greatest value of both cattle and donkeys is in the provision of draft power: in the case of cattle, 64% of their value and in the case of donkeys, over 90%. Unfortunately tillage, especially ploughing requires the most energy, often at a time when animals are in poorest condition, after a long dry season. Not only are animals least able to undertake this heavy work, but many households have inadequate animals to make up a tillage team (Mrema and Mrema, 1993).

2.1.2 The evolution of primary tillage methods

The intensive and continuous use of the plough (or conventional tillage) is often regarded as synonymous with successful crop production. However the plough's use is being increasingly criticised, even though, it remains the most widely practised form of tillage in many parts of the world (Kaumbutho, and Kienzle, 2007). The advantages to using conventional primary tillage that include being well known, reliable, simple and tested technology while disadvantages include inadequate draft power especially for poor households, development of plough pan, increased run-off due to poor soil cover.

Conservation tillage (CT) is now increasingly seen as the way forward whose overall aim is to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource-efficient / resource effective agriculture (Kassam, *et al.*, 2009). CT involves a paradigm shift, which does not involve the plough, often a symbol of agriculture. This normally involves zero-tillage with direct seeding through a permanent soil cover, created through the use of green manure cover crops, or by leaving at least 30% of the last crop as residues on the soil surface to form a permanent or semi-permanent organic soil cover. The function of this cover is to protect the soil physically from sun, rain and wind and to feed soil biota. The soil micro-organisms and soil fauna take over the tillage function and mediate the soil nutrient supply. Mechanical tillage disturbs this process. Therefore, zero or minimum tillage and direct seeding are important elements of CA. At the same time, CA increasingly involves the use of crop rotations (usually cereal-legume), with in-field and between field soil and water conservation measures. It involves a change in the agricultural system, and as such has many benefits that include labour saving, reduction in draft power requirement, increased water infiltration and moisture conservation but with a number of challenges such as weed control challenges, competition for residues particularly with livestock and destruction by termites, inadequate site specific knowledge on the use of component technologies and new pest/disease problems during the transition phase due to change in biological equilibrium (Kaumbutho, and Kienzle, 2007).

2.2 RAKE ANGLE

Rake angle is the angle between the upward face of the point and the horizontal (Figure 2.1). It can also be defined as the forward angle between the face of the tool and the horizontal soil surface.

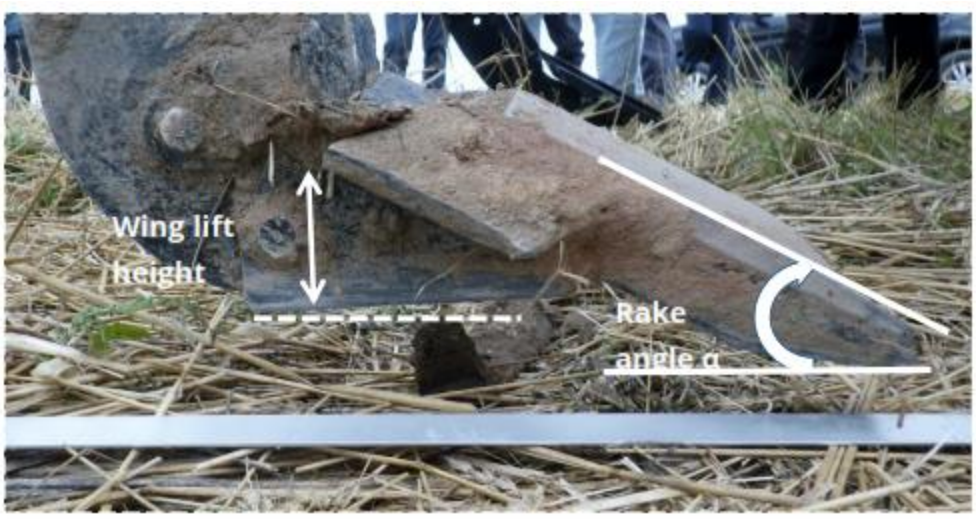


Figure 2.1: Wing lift height and Rake Angle (Source: A guide to successful Subsoiling - CETAB)

The smaller it is, the easier the point can penetrate the soil and the lower its draft resistance. The rake angle can be decreased by increasing the length of the point while maintaining a constant lift height. When the rake angle is too great (which is generally not the case for commercially manufactured subsoilers), the soil is pushed forward rather than being lifted upwards, which compacts the soil ahead instead of loosening it, and increases the draft resistance.

2.3 SOIL COMPACTION

Soil compaction is the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density (Hamza and Anderson, 2005). Soil compaction can reduce crop yields by restricting root development as well as water and air movement in the soil (Batey, 2009). There are many soil factors that determine compactibility, but the water content is the only trait that can be managed to reduce soil compaction in the short term (Nawaz *et al.*, 2012). The dependence of resistance of agricultural soils to compaction on soil water content were defined with the Proctor test, a widely accepted procedure to study compactibility of disturbed soils over a range of soil water contents under a standardized dynamic load(Amanullah *et al*., 2010). Deep soil compaction is difficult to alleviate by tillage and may have long lasting implications for crops production (Hamza & Anderson, 2005) One of the most common methods used to remove compacted soil conditions is sub-soiling (Jin *et al*., 2007).

2.4 RIPPING AND SUB-SOILING

Soil compaction and the consequential drop in productivity due to plough pans is one of the main challenges associated with conventional tillage. Soil compaction reduces crop yields by restricting root development as well as water and air movement in the soil (Batey, 2009). There are many soil factors that determine compactibility, but the water content is the only trait that can be managed to reduce soil compaction in the short term (Nawaz *et al.*, 2012). Deep soil compaction is difficult to alleviate by conventional tillage (Hamza and Anderson, 2005) unless sub-soiling is used (Jin *et al.*, 2007).

Because of the significant draft force required to subsoil compacted profiles, many different types of sub-soilers have been designed and tested (Celik and Raper, 2012) . The shape of the Sub-soiler shank can have a large effect on the required draft and soil disruption. (Raper, 2007) reported that bentleg shanks had the lowest aboveground soil disruption when compared to several straight shanks for non-inversion in-row sub-soiling. This type of shank was found to be suitable for a conservation tillage system. (Reeder and Wood, 1993) reported that a parabolic Sub-soiler required reduced draft compared to a conventional Sub-soiler and a triplex Sub-soiler.

The sub-soiler's point configuration has a large effect on the required draft and soil disruption (McKyes and Maswaure, 1997). Some producers have reported that their draft force and their soil disturbance have been reduced by using a 'splitter point' on their Sub-soiler. No one piece of equipment or configuration works best for all situations and soil conditions, making it difficult to define exact specifications for sub-soiling equipment and operation.

Deep tillage or sub-soiling is a field operation usually performed to break-up compacted layers of soil at depths of 10 to 20 inches. This operation requires very high energy inputs. Thus, it is important that all equipment is properly adjusted and matched to the correct size prime mover to ensure a cost-effective operation. Sub-soiling disrupts compacted soil profiles, improves infiltration, increases soil moisture storage, and allows roots to proliferate downward to obtain adequate soil moisture and potentially improve crop yield (Kaumbutho and Kienzle, 2007). How effectively compacted layers are fractured depends on the soil's moisture, structure, texture, type, composition, porosity, density and clay content. Success depends on the type of equipment selected, its configuration, and the speed with which it is pulled through the ground.

The main purposes of sub-soiling are to increase water infiltration and storage, and to allow easier penetration of the root system (especially tap roots) beneath the ploughing depth (up to 25cm). However, this method is only useful in certain circumstances, and is hence expected to attract only a particular group of users, especially as the Sub-soiler requires at least two strong pairs of oxen. Sub-soiling should be carried out in the dry season, well or just before the onset of the rainy season. The operation cannot be carried out in wet conditions.

2.5 HARNESSING FOR SUBSOILING

Sub-soiling is normally carried out on dry land to break hard pans so it requires high draft forces (Temesgen *et al.*, 2009). Therefore a team of animals should be used, for example four draft oxen. The effective distance between two spanned animals moving abreast depends on how much sub-soiling the operator wants in a particular field (Barwell and Ayre, 1982). If sub-soiling is to be carried out on permanent crop rows similar harnessing to that described for ripping should be used.

2.5.1 Subsequent operations to sub-soiling

Subsequent operations after sub-soiling can be any primary tillage field operation. For conservation tillage, ripping or ripping and mechanical planting is recommended (Raper, 2007).

Like the ripper attachment, the Sub-soiler attachment fits onto any normal I-beam type plough frame. The beam extension which holds the jumper bar and the main beam together and provides for adjustment of the jumper bar for deeper or shallower penetration. A special hitch assembly goes with the attachment. It extends the main beam lengthwise to suit the reaction point geometry of the deep penetrating jumper bar.

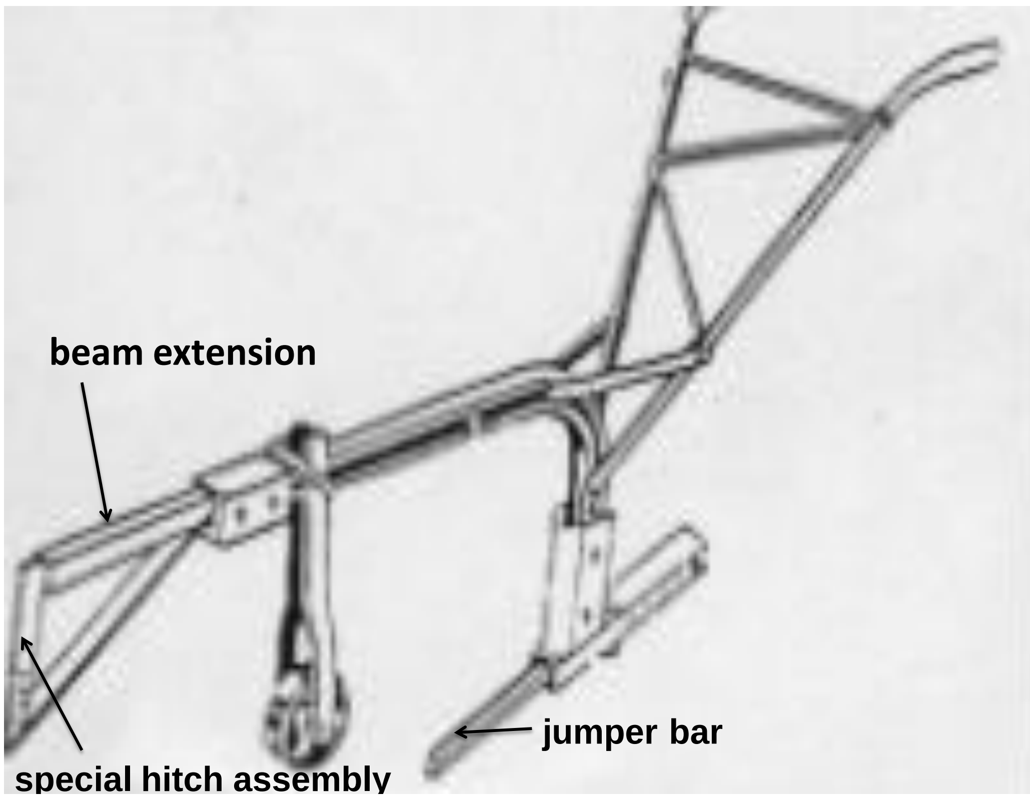


Figure 2.2: Paladama sub-soiler attached on a victory plough frame (Source: Conservation Agriculture: a manual for farmers and extension workers in Africa)

2.6 CRITICAL DEPTH

The critical depth is defined as the maximum working depth at which the soil can be cracked and lifted upwards rather than being laterally compressed. Below this depth, the subsoiler's points compact the soil and smearing often occurs along the channels created by the points (Figures 2.3).

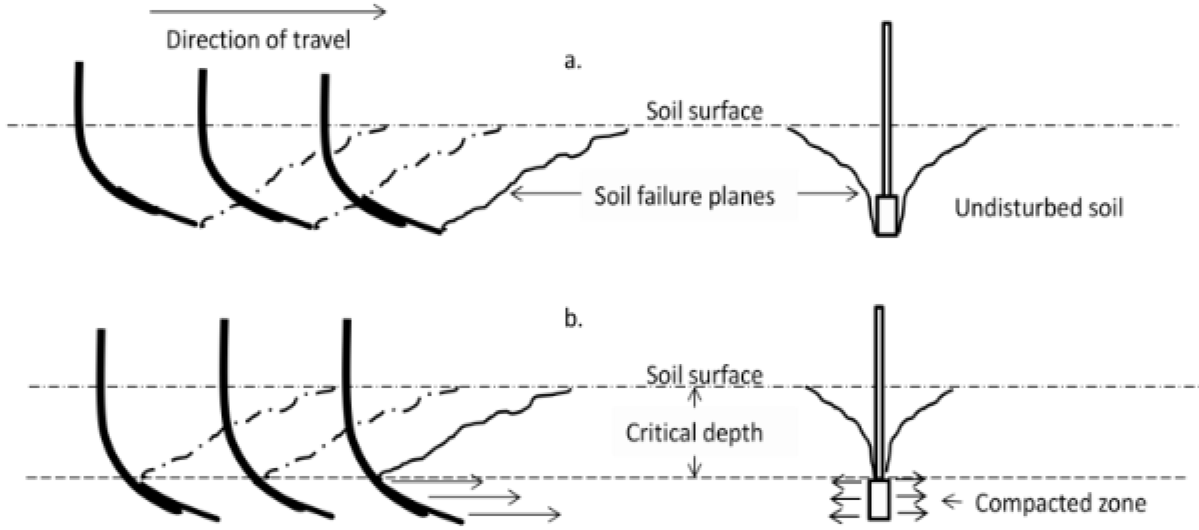


Figure 2.3: Side elevation (left) and cross-section (right) of a narrow tine showing the effects of operating depth on soil disturbance above (a) and below (b) the critical depth. (Source: A guide to successful Subsoiling - CETAB)

The critical depth depends upon the type of implement being used, how it is adjusted and operated, and the prevailing soil conditions. Soil moisture content and density are particularly important in affecting the confining resistance. In his study, Spoor (2006) demonstrated that the greater the confining resistance, the shallower the critical depth and the vice versa. He further recommended that in situations where the critical depth is shallower than the desired working depth the following implement and operational modifications can be made to increase the critical depth: increase the width of the point; add wings, thus increasing the effective width of the point; increase the lift height of the wings; decrease the rake angle.

2.7 SOIL MOISTURE

Soil moisture is the amount of water present in the soil and is the water that plants access for survival. Soil moisture information is of great importance for various purposes such as irrigation scheduling, crop yield prediction, nutrient management and fertilization scheduling, as well as pesticide application and management (McMillan *et al.*, 2012). A dry sandy loam would have a much greater draft and therefore require more power to plough than a moist sandy loam. This is due to the lubricating effect of moisture films surrounding soil particles and also due to a decrease in soil strength imparted by the moisture (Zhang *et al.*, 2001). On the other hand, fine textured soils require extra power to plough and may be impossible to plough when moisture is too low. To save power and maximize effectiveness, the timing of tillage should coincide with the time when soil is most friable.

2.8 SOIL BULK DENSITY

The dry bulk density of a soil gives an indication of the soil strength and thus the resistance presented to tillage implements or plant roots as they penetrate the soil (Lampurlanés and Cantero-Martínez, 2003). Soil bulk density is defined as the mass per unit volume of dry soil in its undisturbed state. For a soil of a given particle density, bulk density is directly related to total porosity, the space available in the soil for gas and water movement and root development. 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). Oven dried soil bulk density is calculated using the formula below.

Oven dried bulk density

$$D_b = \frac{M}{\pi R^2 L} \qquad [2.1]$$

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.

2.9 SOIL SHEAR STRENGTH

Soil shear strength is the torsional load the soil structure can support without any further compression (Zhang *et al.*, 2010). This is of agricultural and engineering importance in maintaining the soil structure against compaction by animals and agricultural machinery as well as in specifying cultivation implements design to change the structure of the soil and alleviation of soil compaction. Soil strength is determined by the degree of cohesion and internal friction existing between soil particles (Horn *et al.*, 1994) . The strength of the soil has a bearing on root penetration and seedling emergence.

Soil shearing strength is made up of a cohesive component as well as a frictional component (Luding, 2008). Empirically the soil shear strength is usually defined by the Mohr – Coulomb equation below as cited in (Noor and Hadi, 2010)

$$\tau = C + \sigma \tan \emptyset \quad [2.2]$$

Where:

τ = Soil Strength,

C = Soil Cohesion,

σ = Normal Stress and

$\tan \emptyset$ = Coefficient of friction.

Several factors have been found to influence the strength of the soil (Hamza and Anderson, 2005). Davies (1985) investigated the effect of organic matter on shear strength. Organic matter content was found to increase the shear strength of soil by as much as 10kPa. This was explained by Huat (2006) to be due to increase in binding of soil mineral components together by organic matter. However high organic matter values results in a decrease in shear strength.

Moisture content has been found to be an influencing factor in soil strength values. The shear strength was found to be lowest at the highest natural soil moisture content (Fan and Su, 2008). Drainage in agriculture increases the bearing capacity of the soil (McMillan, 2012). The mean shear strength was found to be significantly correlated to the volumetric water content (Davies, 1985). Cetin *et al.* (2007) found that peak soil cohesive angle values occurred at intermediate moisture content for cohesive soils. A linear increase in friction angle with increasing moisture content independent of density for Silty loam soil was observed by (Máthé *et al.*, 2010). An increase in density of the soil has also been shown to increase the shear strength parameter of the soil (Zhang *et al.*, 2001). So moisture content has an important effect on the strength of the soil and should be accounted for.

2.10 PENETRATION RESISTANCE

The use of penetration resistance studies in tillage studies is an area of interest for researchers (Lampurlanés and Cantero-Martínez, 2003). Herrick and Jones (2002) characterized the depth and persistence of soil loosening induced changes by penetration resistance measurements. The penetration resistance measurements quantified depth, degree and persistence of soil loosening and potential soil rooting depth. He also illustrated that residual tillage effects may also be evaluated by determining the changes in depth to a penetration resistance of 1.5 MPa over the growing season. The spatial and temporal variability of soil properties following tillage was investigated by Tsegaye and Hill (1998). Cone penetrometer readings provided information which allowed a valid comparison of relative soil hardness or mechanical impedance. He observed significant difference in cone index (CI) at all depths.

Motavalli *et al.* (2003) investigated the use of cone index in soil compaction studies. They concluded that cone index values developed for different soil types were useful in decision making by the farmer with regards to the implement type and cultivation practices that best suits the soil for a particular crop. Máthé *et al*. (2010) investigated the influence of moisture and density on cone index. They found that the maximum cone index occurred at a moisture content producing the maximum shear strength as determined by triaxial tests. At low moisture content, an exponential relationship was observed between cone index and dry density and the rate of increase decreased with increasing moisture content.

2.11 DRAFT POWER

Draft power is described in units of horsepower (hp) that was first described by James Watt in England in the late eighteenth century (Morris, 2007). Watt found that an average horse could lift 366 lb of coal out of a mine at the rate of one foot per second (366 ft-lb/sec).

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

$$D_p = F \text{ x } \frac{D}{T} \qquad [2.3]$$

Where: D_p = Draft power (watts),

F = Force (Newton),

D = Distance (metres) and

T = Time (seconds)

Power delivery is increased by increasing force or speed which reduces the time required to complete a task. In tillage, draft is the force required to move an implement in the direction of travel (Harrigan and Roosenberg, 2002). Total draft of most tillage implements is influenced by the resistance to soil and crop residues. Under normal conditions wide variations in draft of tillage tools are common both within and between soil textural groups due to soil moisture, soil strength, residue cover and other physical characteristics (Licht and Al-Kaisi, 2005). Dry, consolidated soil generally provides greater resistance to tillage tools than the same soil when moist and friable (Daraghmeh *et al.*, 2009). The tractive surface in the field can vary from firm and compact to soft or muddy. Loose soil increases slippage of the tractor wheels and, draft increases when moving up a slope. Tillage draft also depends upon the depth of tillage (Al-Suhaibani, 2010). Some tillage tools are used for both primary and seedbed tillage. Primary tillage is an initial soil working operation designed to shatter consolidated soil and bury crop residue that can require more power than secondary tillage.

In estimating tillage draft, soils can be conveniently categorized as fine, medium or coarse rather than using the traditional but more confusing classifications such as clay, sandy-loam or silty-clay-loam. Fine textured soils can be considered as high in silt and clay, medium textured are loamy soils and coarse textured soils are sandy soils. Implement draft generally increases in going from coarse to fine textured soils.

2.12 SUMMARY OF LITERATURE REVIEW

In most Sub-Saharan African countries, animal traction for tillage and wheeled transport was introduced during the colonial period. The aim was to increase agricultural production in the colonies by teaching the indigenous population how to use work animals for plowing. In 1903, European farmers and traders started to settle in the Machakos District of Kenya. They used heavy plows that required teams of six animals. There was no formal promotion of animal traction, but plows were available from trading stores. The increase in farm size and cash-crop production was the motivating factor for the high rate of adoption. Statistics show that human power still predominates over much of the developing world, contributing over 70% of power requirements. At the same time draft animals contribute nearly a quarter of power needs and tractors only 6%.

The intensive and continuous use of the plough (or conventional tillage) is often regarded as synonymous with successful crop production. However the plough's use is being increasingly criticised, even though, it remains the most widely practised form of tillage in many parts of the world. Increased field traffic during tillage is believed to be the main cause of soil compaction. This can be mitigated through sub-soiling. Sub-soiling disrupts compacted soil profiles, improves infiltration, increases soil moisture storage, and allows roots to proliferate downward to obtain adequate soil moisture and potentially improve crop yield. How effectively compacted layers are fractured depends on the soil's moisture, structure, texture, type, composition, porosity, density and clay content. Success depends on the type of equipment selected, its configuration, and the speed with which it is pulled through the ground.

3.0 THEORETICAL FRAMEWORK

3.1 PHYSICAL SOIL PARAMETERS PERTINENT TO TILLAGE

Physical soil parameters have a direct bearing on the power requirement for any tillage operation (Horn *et al.*, 1994). Table 3.1 shows the sources of materials for the soil physical parameters. In this experiment, Particle Soil Distribution (PSD), Texture, Moisture content, Wet and Dry bulk densities, Soil compaction, Penetration resistance and Shear stress were considered.

Table 3.1: Material sources for the physical parameters

No.	**Physical Properties**	**Source / Authors**
1	Particle Size Distribution	Okalebo, *et al.* (2002), Osman, (2014)
2	Soil Texture	Okalebo, *et al.* (2002), Okalebo, *et al.* (2002)
3	Soil Moisture Content	Gardner, (1986), Daraghmeh *et al.* 2009
4	Bulk Density	Zhang *et al.* 2001, Bitzler and Tugel, (2002)
5	Compaction	Mortvedt, (1996), Mckyes and Maswaure, (1997), Mapfumo and Chanasyk, (1998), Motavalli *et al.* (2003) and Amanullah *et al.*, (2010)
6	Penetration Resistance	Bradford, (1980), Perumpral, (1987), Onwuala and Watts, (1998), Herrick and Jones., (2002) and Dexter, *et al.* (2007)
7	Shear Strength	Payner, (1956), Cohron, (1963), Osman, (1964), Sall berg, (1965), Mckyes, (1985), Kirby and Ayers, (1993) and Zhang *et al.* 2001

3.1.1 Particle Size Distribution

Particle Size Distribution (PSD) also known as Grain-size analysis is a process in which the proportion of material of each grain size present in a given soil is determined. The grain-size distribution of coarse grained soils is determined directly by sieve analysis, while that of fine-grained soils is determined indirectly by hydrometer analysis. The grain-size distribution of mixed soils is determined by combined sieve and hydrometer analysis. The percentage of material by weight retained on the various sieves is computed as follows:

$$\text{Percentage Retained} = \frac{\text{Weight in grams retained on a sieve}}{\text{Total weight in grams of oven-dry sample}} \times 100 \qquad [3.1]$$

The hydrometer method of analysis is based on Stoke's law, which relates the terminal velocity of a sphere falling freely through a fluid to the diameter. The relation is expressed according to the equation

$$v = \frac{\gamma_s - \gamma_f}{1800\mu} \qquad [3.2]$$

Where υ = Terminal velocity of sphere in cm/s

γ_s = Density of sphere, gms per cm^3

γ_f = Density of fluid, gms per cm^3

μ = Viscosity of fluid, gms-sec per cm^3

It is assumed that Stoke's law can be applied to a mass of dispersed soil particles of various shapes and sizes. The hydrometer is used to determine the percentage of dispersed soil particles remaining in suspension at a given time.

3.1.2 Soil Texture

Soil texture is a qualitative classification tool used in both the field and laboratory to determine classes for agricultural soils based on their physical texture. The classes are distinguished in the field by the "textural feel" which can be further clarified by separating the relative proportions of sand, silt and clay using grading sieves: The Particle-size distribution (PSD). The class is then used to determine crop suitability and to approximate the soils responses to environmental and management conditions such as drought or calcium (lime) requirements. A qualitative rather than a quantitative tool it is a fast, simple and effective means to assess a soil's physical characteristics.

3.1.3 Moisture content

The moisture content of soil can be evaluated by direct as well as indirect methods (Fan and Su, 2008). The direct methods are those that involve driving away water by evaporation, leaching or chemical reaction then determine the amount of water lost. This is accomplished by determining the weight difference of the sample, collection of the distillate or measuring the reaction products displaced from the sample. So in either case separation of water from the soil to quantify the amount present is involved. Indirect methods involve the use of certain soil properties either physical or chemical that change to some extent with moisture content or measuring a property of some object placed in the soil which establishes an equilibrium condition with the soil. This may be neutron scattering, electrical or thermal properties. To calculate the moisture content of the soil as a percentage of the dry soil weight, the formula 3.3 is used.

$$MC\% = \frac{W_2 - W_1}{W_3 - W_1} \times 100 \qquad [3.3]$$

Where:

W_1 = Weight of tin (g)

W_2 = Weight of moist soil + tin (g)

W_3 = Weight of dried soil + tin (g)

3.1.4 Bulk Density

Bulk density is an indicator of soil compaction. It is calculated as the dry weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles (Ditzler and Tugel, 2002). Bulk density is typically expressed in g/cm^3. Bulk density is dependent on soil texture and the densities of soil mineral (sand, silt, and clay) and organic matter particles, as well as their packing arrangement. As a rule of thumb, most rocks have a bulk density of 2.65 g/cm^3 so ideally, a medium textured soil with about 50 percent pore space will have a bulk density of 1.33 g/cm^3 (Ditzler and Tugel, 2002). Generally, loose, porous soils and those rich in organic matter have lower bulk density. Sandy soils have relatively high bulk density since total pore space in sands is less than that of silt or clay soils. Finer-textured soils, such as silt and clay loams, that have good structure have higher pore space and lower bulk density compared to sandy soils. Bulk density typically increases with soil depth since subsurface layers have reduced organic matter, aggregation, and root penetration compared to surface layers and therefore, contain less pore space. Subsurface layers are also subject to the compacting weight of the soil above them.

Bulk density is changed by crop and land management practices that affect soil cover, organic matter, soil structure, and/or porosity. Plant and residue cover protects soil from the harmful effects of raindrops and soil erosion. Cultivation destroys soil organic matter and weakens the natural stability of soil aggregates making them susceptible to damage caused by water and wind (Blanco and Lal, 2010). When eroded soil particles fill pore space, porosity is reduced and bulk density increases. Cultivation can result in compacted soil layers with increased bulk density, most notably a “plough pan”. Livestock and agricultural and construction equipment exert pressure that compacts the soil and reduces porosity, especially on wet soils.

Bulk density reflects the soil’s ability to function for structural support, water and solute movement, and soil aeration. Bulk densities thresholds in Table 3.2 indicate impaired function. Bulk density is also used to convert between weight and volume of soil. It is used to express soil physical, chemical and biological measurements on a volumetric basis for soil quality assessment and comparisons between management systems. This increases the validity of comparisons by removing error associated with differences in soil density at time of sampling.

Table 3.2: General relationship of soil bulk density to root growth based on soil texture.

Soil Texture	**Ideal bulk densities from plant growth (g/cm^3)**	**Bulk densities that restrict root growth (g/cm^3)**
Sandy	< 1.60	> 1.80
Silty	< 1.40	> 1.65
Clayey	< 1.10	> 1.47

Source: Soil Quality Indicators, USDA Natural Resources Conservation Services

3.1.5 Compaction

Soil compaction is the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the BD (Mortvedt, 1996). Soil compaction of agricultural land is an important form of physical land degradation. The continuous use of implements for years together develops a hard pan underneath which hinders the movement of water and inhibits growth and yield of crops (Nawaz et al., 2012). Hard pan prevent roots of many upland crops from penetrating into the deeper soil layer. Hence to break the soil compaction and hard pan deep tillage plays a vital role (Amanullah, et al., 2010). The compaction produced by mechanical land clearing can negatively affect the crop yields. There are many soil factors that determine compactibility, but the water content is the only trait that can be managed to reduce soil compaction in the short term (Dexter et al., 2007). The dependence of resistance of agricultural soils to compaction on soil water content were defined with the Proctor test, a widely accepted procedure to study compactibility of disturbed soils over a range of soil water contents under a standardized dynamic load (Motavalli et al., 2003). In the Proctor test, the BD is a function of soil water content, and it is used to determine the water content at which maximum BD, known as the optimum water content, occurs; in agriculture this is called ‘‘critical water content’’ because soil compaction is undesirable (McKyes and Maswaure, 1997). The function described does not constitute a single characteristic curve for a given soil type, but a family of curves for different compaction efforts. For a greater compaction force, the curve is shifted upward and leftward, indicating higher attainable ‘‘maximum BD’’ at lower values of ‘‘critical moisture’’.

3.1.6 Penetration Resistance

The soil resistance to penetration by cone penetrometer defined as the normal force divided by the area of the cone base, has been used by several researchers to characterize different aspects of soil quality (Dexter, et al., 2007). A considerable amount of information regarding soil properties 'can be obtained by use of either in situ or laboratory penetrometer measurements. A wide variety of penetrometer exists and a comprehensive review of these and their uses was done by Dexter, et al. (2007). Penetrometers differ in terms of their apex angles and base area, mode of operation (hand or dynamic) and rate of operation. The use of penetrometer has been found to have the following advantages (Onwualu and Watts, 1998).

1) Easy, rapid, and economical.

2) Provides test data that-can be analyzed easily.

3) Good tools to investigate sands where undisturbed sampling is difficult.

However they do not sample for direct observation and its difficult for hand driven penetrometer to control a standard rate of penetration. Herrick and Jones (2002) cited the lack of clarity in penetrometer data analyses and interpretation as a problem due to the need for standards for probe characteristics and procedures.

3.1.7 Shear Strength

The shear strength of a soil is its resistance to shearing stresses. It is a measure of the soil resistance to deformation by continuous displacement of its individual soil particles. Shear strength in soils depends primarily on interactions between particles (Zhang *et al.,* 2001). Huat (2006) observed that shear failure occurs when the stresses between the particles are such that they slide or roll past each other.

Several methods are available for measuring soil strength properties. These include the vane shear test, the direct shear test, the triaxial compression and unconfined compression test, (Zhang *et al.*, 2010). The soil strength results obtained depend not only on the soil conditions but also on the test method employed. This is so because of the variation in soil preparation requirements as well as the steps in testing of the soil specimen.

In tillage studies or any earthmoving studies it is a requirement to produce large volumes of data rapidly (Noor and Hadi, 2010). The shear graph satisfies this requirement by measuring the shear strength in situ. It has several advantages such as less time requirement, data reliability and less soil disturbance. It has been used in many tillage studies with considerable success, (Payne, 2009; Osman, 2014; and Noor and Hadi, 2010).

The measurement of soil cohesion and soil internal friction angle was carried out using a soil Sheargraph described by Cohron (1963), Figure 3.1. The design consists of a shearhead with grousers (blades) inside to grip the soil. This enables the operator to apply 105 kPa (15 lb/irr'): normal pressure comfortably. It also has a calibrated spring which deflects when the soil is in shear failure, a recording drum on which a recording pen writes to indicate the values of the shear and normal pressures applied. It also has a handle for the operator to hold and apply the required combination of pressures.

In addition to the cohesive and frictional components of the soil the draft force also depends on the extent to which the soil sticks to the blade (adhesion) and the soil to metal friction angle. To measure these parameters the Cohron Sheargraph was also used. To do this a standard steel metal plate designed to fit the size of the shearhead was fitted into it and the procedure described for measuring cohesion and soil internal friction angle repeated to obtain a similar graph. In this case the intercept on the shear stress axis gives the adhesion and the angle between the graph and the horizontal gives the soil to metal friction angle (B).

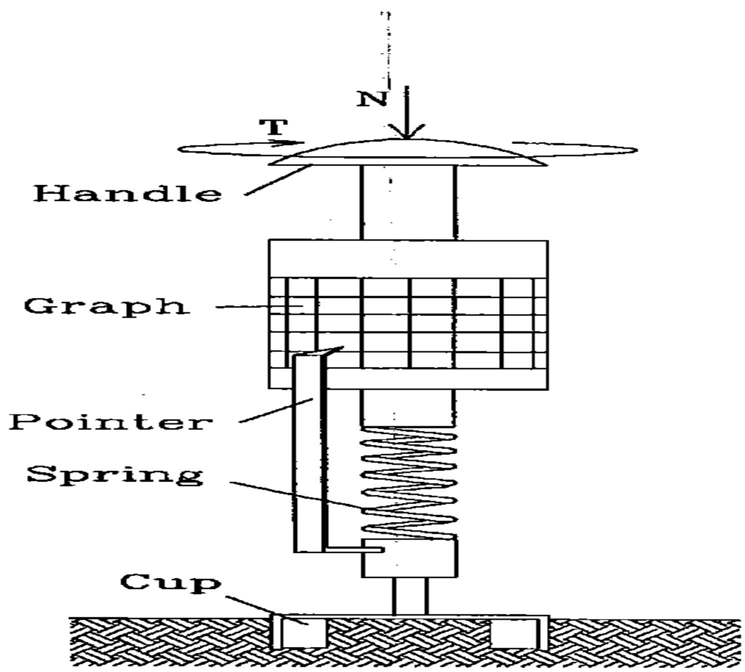


Figure 3.1: Cohron Sheargraph (Source; Agricultural Engineering Soil Mechanics)

3.2 SUBSOILER PARAMETERS PERTINENT TO TILLAGE.

3.2.1 Subsoiler Geometry

The shape of the Subsoiler shank can have a large effect on the required draft and soil disruption. (Raper, 2007) reported that bentleg shanks had the lowest aboveground soil disruption when compared to several straight shanks for non-inversion in-row subsoiling. This type of shank was found to be suitable for a conservation tillage system. (Reeder and Wood, 1993) reported that a parabolic Subsoiler required reduced draft compared to a conventional Subsoiler and a triplex Subsoiler.

The subsoiler's point configuration has a large effect on the required draft and soil disruption (McKyes and Maswaure, 1997). Some producers have reported that their draft force and their soil disturbance have been reduced by using a 'splitter point' on their Subsoiler. No one piece of equipment or configuration works best for all situations and soil conditions, making it difficult to define exact specifications for subsoiling equipment and operation.

3.3 MODELING

Scientific modeling is an activity, the aim of which is to make a particular part or feature of the world easier to understand, define, quantify, visualize, or simulate by referencing it to existing and usually commonly accepted knowledge. It requires selecting and identifying relevant aspects of a situation in the real world and then using different types of models for different aims, such as conceptual models to better understand, operational models to operationalize, mathematical models to quantify, and graphical models to visualize the subject. Modeling is an essential and inseparable part of scientific activity, and many scientific disciplines have their own ideas about specific types of modeling. A useful model is one that captures the proper elements of reality with acceptable accuracy.

3.3.1 Regression Analysis

Regression analysis is a statistical tool for the investigation of relationships between variables. Usually, the investigator seeks to ascertain the causal effect of one variable upon another. In statistics, linear regression is an approach of modelling the relationship between a scalar dependent variable y and one or more explanatory variables denoted x. In linear regression, data is modelled using linear predictor functions, and unknown model parameters are estimated from the data. These type of models are referred to as linear models. Most commonly, linear regression refers to a model in which the conditional mean of y given the value of x is an affine function of x. Less commonly, linear regression could refer to a model in which the median, or some other quantile of the conditional distribution of y given x is expressed as a linear function of x. Like all forms of regression analysis, linear regression focuses on the conditional probability distribution of y given x, rather than on the joint probability distribution of y and x, which is the domain of multivariate analysis.

Linear regression models are often fitted using the least squares approach, but they may also be fitted in other ways, such as by minimizing the "lack of fit" in some other norm (as with least absolute deviations regression), or by minimizing a penalized version of the least squares loss function as in ridge regression (L2-norm penalty) and lasso (L1-norm penalty). Conversely, the least squares approach can be used to fit models that are not linear models. Thus, although the terms "least squares" and "linear model" are closely linked, they are not synonymous.

For accuracy a regression line also called a line of best fit or trend line is calculated using a least square formula. The least square regression line minimizes the sum of the squared errors.

The statistical linear regression equation is:

$$y = b_0 + b_1 x + e \qquad [3.4]$$

Where:

y = the y – axis variable,

x = the x- axis variable,

b_0 = the intercept (value of y when x = 0)

b_1 = the slope of the line

e = Random Error or residue

The Least Square Regression Line Equation is thus stated as:

$$\hat{y} = b_o + b_1 x \qquad [3.5]$$

Where:

$\hat{y}$ = estimated or predicted y value

The b_0 and b_1 are obtained by finding the values of b_0 and b_1 that minimize the sum of the squared errors using equation B

$$\sum e^2 = \sum (y - \bar{y})^2 = \sum \left(y - (b_o + b_1 x)\right) \qquad [3.6]$$

The formulas for both b_1 and b_0 are presented in equations R and T

$$b_1 = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2} \qquad [3.7]$$

$$b_0 = \bar{y} - b_1 \bar{x} \qquad [3.8]$$

3.3.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a collection of statistical models used in order to analyze the differences between group means and their associated procedures, such as "variation" among and between groups. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal (Saville, 2003).

4.0 MATERIALS AND METHODS/METHODOLOGY

4.1 INTRODUCTION

The study was conducted at the University of Nairobi, College of Agriculture and Veterinary Sciences, Kabete Campus which lays on 01^{o}14.891'S , 036^{o}43.707'E and elevation of 1849 metres amsl. It is in Nairobi County.

Figure 4.1: Map showing the location of the experimental site.

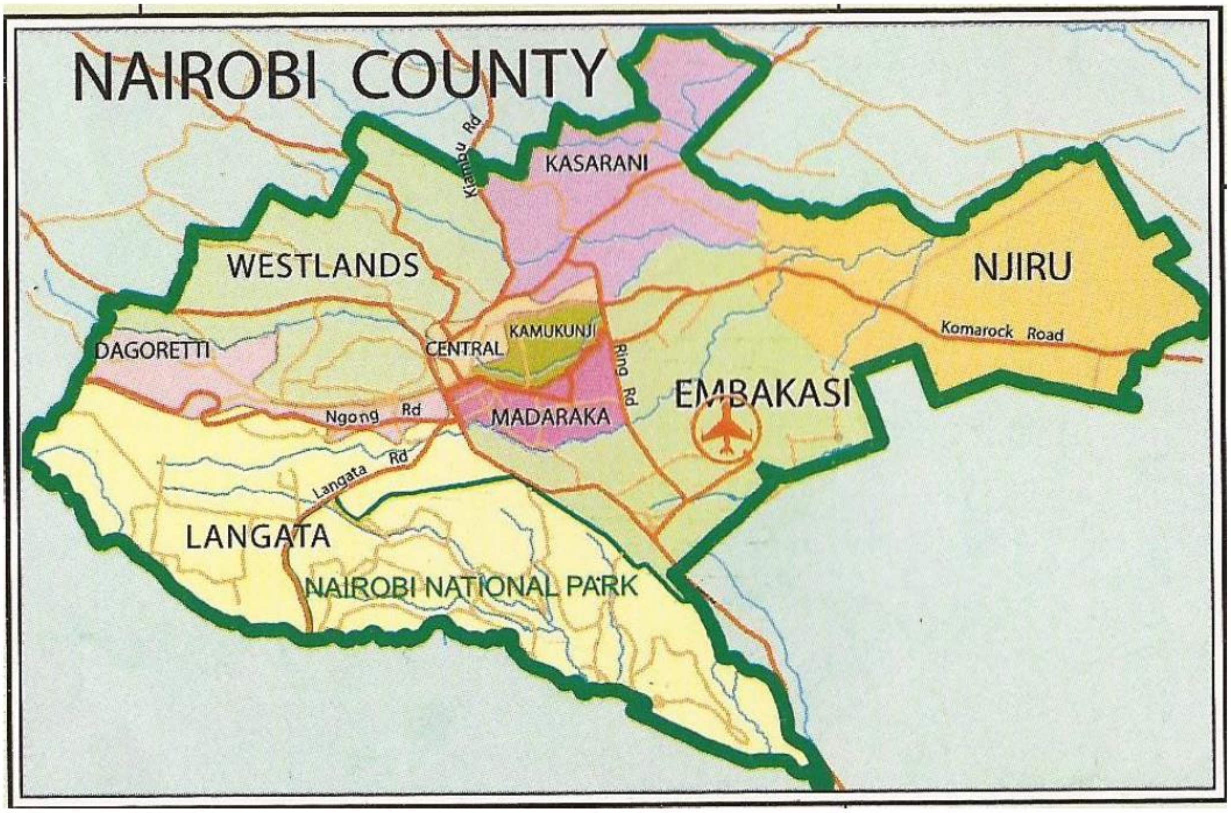


Figure 4.2: Constituencies of Nairobi County

The county is divided into four broad topographical zones viz. Upper Highland, Lower Highland, Upper Midland and lower Midland zone. The annual rainfall varies with altitude, with higher areas receiving as high as 2,000 mm and lower areas of Juja constituency receiving as low as 600 mm and an average of 1200 mm. The mean temperature in the county is 26^0 C with temperature ranging from 7.1^0C in the upper highlands to 34^0C in the lower midlands. July and August are the months during which the lowest temperatures are experienced, whereas January to March is the hottest months. The county is covered by three broad categories of soils which are high level upland soils, plateau soils and volcanic footbridges soils. They are basically Nitisols. Figure 4.2 shows a soil distributions map and its environs.

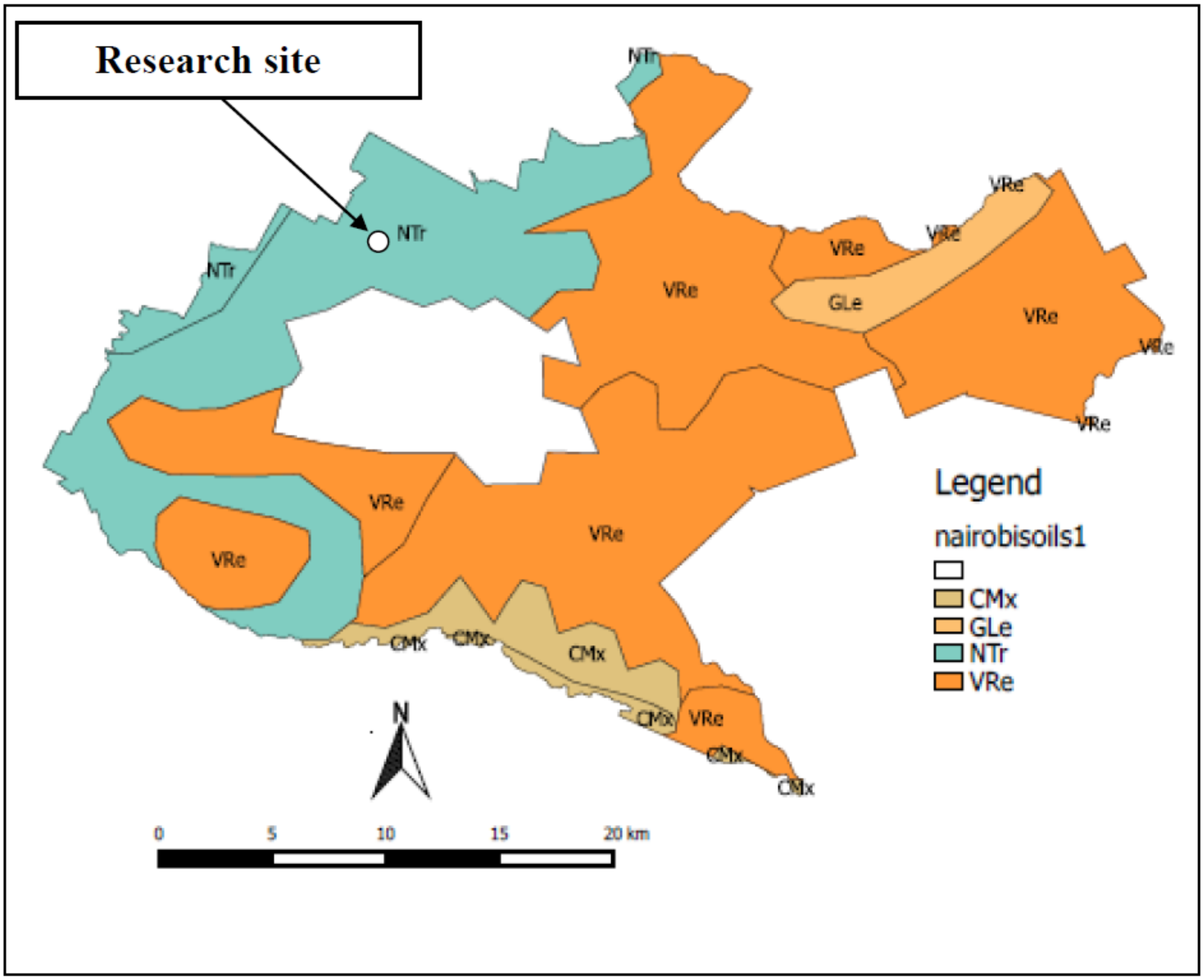


Figure 4.3: Soil Map of Nairobi County Showing the Experimental Site.

These soils are of varying fertility levels with soils from high-level uplands, which are from volcanic rocks being of high fertility.

Soil physical properties (soil moisture, texture, structure, bulk density, shear stress and penetration resistance) were determined prior to the experiment.

4.2 DETERMINATION OF SOIL PHYSICAL PARAMETERS

4.2.1 Determination of Soil Texture

To determine soil texture, soil samples were air dried and passed through a 2mm sieve. 51 grams the sample was transferred into a baker and 10ml of hydrogen peroxide (dispersing agent) added to it. The mixture was then shaken lightly with distilled water being added slowly to reduce the volatility. The mixture was then allowed to digest for a period of 3 days. This was to enable the destruction of organic matter within the sample. After this, 5 ml of hydrogen peroxide was added and given a day to settle. The mixture was then transferred to a 300ml shaking bottle. 50ml of Calgon solution (A mixture of 7 gms sodium carbonate and 33gms of sodium hexametaphospahate in a litre of distilled water) and 200 ml of distilled water was then added. The shaking bottle was the mount on a horizontal shaker (end to end shaker) for 6 hours continuously. The mixture was the transferred to 1000 ml cylinder and topped to mark with water. The suspension was then stirred with a plunger for 60 seconds and a hydrometer was carefully lowered into it. Hydrometer reading, H_1, was taken after 40 seconds. The hydrometer was carefully removed and the solution temperature, (T1). A separate cylinder (1000 ml), was filled with distilled water and the hydrometer blank (B1) and temperature readings taken respectively. After 3 hours, readings were taken to record the hydrometer reading (B2), temperature reading (T2) and of the blank. The hydrometer is calibrated at 20^{o} C. For this reason, a correction has to be made when the temperature is higher or lower.

To calculate the percentage of various soil particles in the sample, Bouyoucos Hydrometer Method was used.

4.2.2 Determination of Soil Particle Size Distribution

A soil sample weighing 500gms was taken and air-dried, after which the aggregations present in the sample were thoroughly broken up with the mortar and pestle. A representative sample was then obtained by dividing, using the sample splitter. The sample was oven-dried at 110 ^{0}C, allowed to cool and then weighed. The samples were passed through various sieves with recordings being made in a data entry sheet. Formula 3.1 and 3.2 were used to determine the distribution of particles in the soil sample.

4.2.3 Determination of Soil Moisture Content

A direct method, gravimetry, with oven drying described by Gardner (1986) was used in the determination of moisture content. A soil auger of diameter 20 mm and 300 mm length was used to sample the soil at different depths. The samples were enclosed in sampling cans immediately to minimize evaporation from the sample. Sampling was done at 100 mm, 200mm and 300mm depths. This was done to cover the entire depth range encountered in normal tillage operations. The soil samples were weighed on a digital scale in the laboratory and oven dried at 105°C for a period of 24 hours. The samples were then reweighed and the weight of each marked can determined. The moisture content was calculated from equation 4.4.

$$W = \frac{\text{Weight of wet soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}} \qquad [4.1]$$

Plate 4.1: Soil sampling from the experimental field

4.2.4 Determination of Bulk Density

To determine initial soil bulk density for top-soil, soil cores were collected using stainless steel rings (0-15 cm). The full cylinder or the soil from the cylinder was placed in a weighing tin and weighed. The weight of the wet soil plus tin plus cylinder was recorded as W1. The weight of the tin was recorded as W2 and the weight of the cylinder as W3. These weights (W2 and W3) were measured before sampling. The samples were then dried in an oven at $105^{O}C$ for 48 hours. The weight of the oven dry sample, tin and cylinder were recorded as W4. The bulk density was then calculated by:

$$D_b = \frac{W4 - W2 - W3}{\text{Volume of cylinder}}$$ [4.2]

4.2.5 Determination of Penetration Resistance

Topsoil (0-10 cm depth) penetration resistance was measured in the last season (long rains '09) using a hand ring cone penetrometer (Type 1b) (0.05 cm cone diameter and 1.0 kg cm^{-2} spring) in three positions within each plot. The moveable penetrometer ring was adjusted to zero and the cone pushed at a constant speed in to the soil. A reading was taken showing maximum compression of the spring and penetration resistance determined using the equation 4.6.

$$PR = D \text{ x } \frac{F}{d}$$ [4.3]

Where:

PR = Penetration resistance (kg cm^{-2}),

D = Penetrometer sliding distance (cm),

F = Spring kilogram force (kg cm^{-2}) and

d = Cone diameter (cm).

4.2.6 Calculation of soil porosity

The soil porosity for the different soil depths was calculated using equation 4.7.

Soil Porosity (f) = $1-(P_b/P_s)$ [4.4]

Where:

P_b is the dry soil bulk density and P_s is the soil particle density taken as 2.65 gcm^{-3}

4.2.7 Determination of Shear Strength

The measurement of soil cohesion and soil internal friction angle was carried out using a soil Sheargraph described by Cohron (1963), Figure 3.1. The design consists of a shearhead with grousers (blades) inside to grip the soil. This enabled the operator to apply 105 kPa (15 lb/irr'): normal pressure comfortably. It also had a calibrated spring which deflects when the soil is in shear failure, a recording drum on which a recording pen writes to indicate the values of the shear and normal pressures applied. It also had a handle for the operator to hold and apply the required combination of pressures.

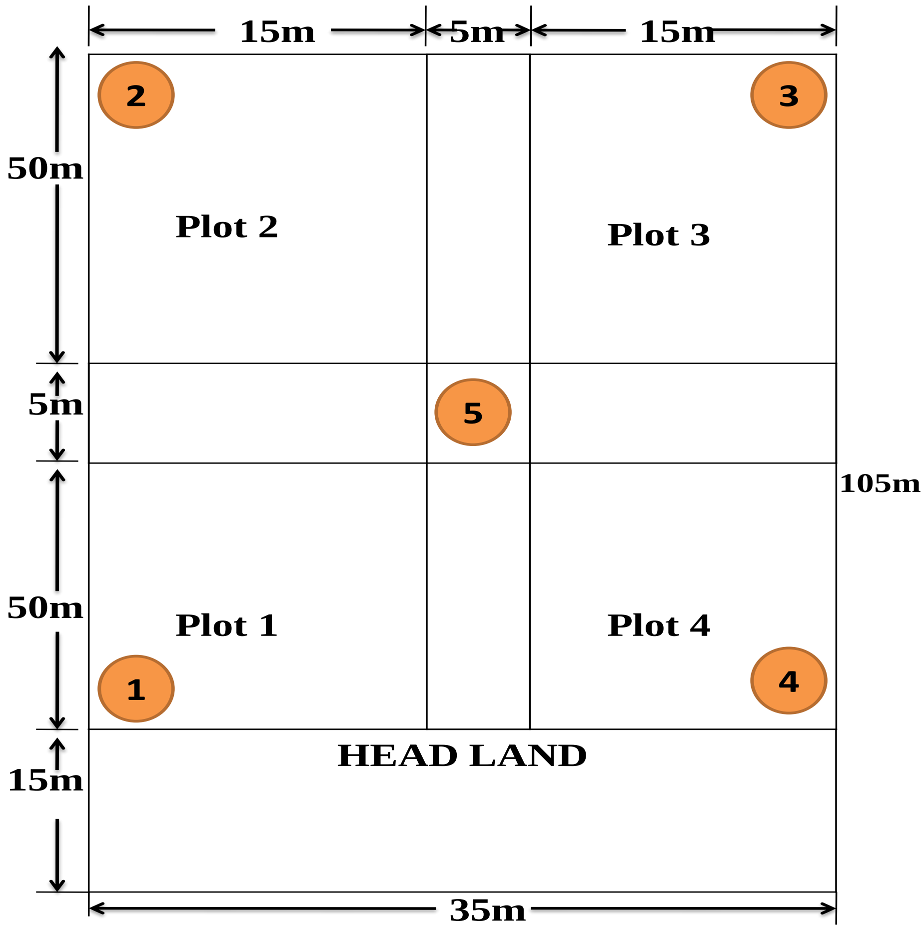
The operator forced the circular shear head into the soil so that the grousers grip the soil and then applied a known amount of normal pressure. He then twisted the handle to apply a shearing force on to the soil. At the point of failure the shear head started to turn. The operator took note of this point by making a mark on the recording drum to which is attached a special paper indicated the relationship between normal and shear pressure. Varying amounts of normal pressures were applied and a mark was made at each point when the soil started to fail. A straight line drawn through the points represent the soil failure line or the soil strength.

Plate 4.2: In-situ shear stress determination.

4.3 FIELD EXPERIMENT

4.3.1 Experimental Layout

An experimental plot of 50m long by 15m wide was used for each treatment. A block of 30m long by 15m wide was used as a practice area prior to the beginning of the experimental runs to enable the tractor and the implement reach the required speed and depth.



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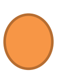


Soil Sampling Pits

Figure 4.4: Experimental field lay-out.

4.3.2 Experimental Subsoiler

To carry out this experiment, a special sub-soiler was fabricated which could be mounted on a two wheeled frame that was able to be hitched on the top link and drawbar of the tractor (Appendix VI). It consisted of a clamp made from two 9mm plates joined together to form two semi-circular flanges. Seven holes of 10mm internal diameter were drilled through the flanges to enable it be attached on the two-wheeled frame. The top hole was the pivot while the remaining ones allowed for the variation of the sub-soiler's rake angles of 30^o, 40^o, 50^o, 60^o and 70^o without necessarily removing the whole tool from the mounting frame (Plates 4.3 and 4.4). The sub-soiler was fitted with a 430mm hexagonal jumper bar to allow for depth adjustment.

Plate 4.3: Fabricated Experimental Sub-soiler

Plate 4.4: A sub-soiler mounted on the two wheeled frame for 60^o rake angle

4.3.3 Field Data Collection

Two tractors were used in this experiment. The first tractor towed the second tractor with a dynamometer attached between them to measure draft. The Subsoiler was hitched on the second tractor which was in free gear. Readings from the dynamometer were taken by a digital datalogger. The tractors were used in this study instead of draft animals so as to improve stability and avoid fluctuation of the two experimental speeds of 0.6 m/s and 1.2 m/s. These are the lowest speeds a draft animal can achieve while drawing a land preparation tool.

The parameters to be investigated for the draft measurement were forward speed and depth of subsoiling. For the five rake angles of 30^o, 40^o, 50^o, 60^o and 70^o, two forward speeds of 0.6m/s and 1.2m/s and three depth ranges of 0 – 10cms, 0 – 20cms and 0 – 30cms were used in combination for 30 treatments with four replicas. Depth was measured as the vertical distance from the top of the undisturbed soil surface to the implements deepest penetration depth.

Plate 4.5: A hitched Sub-soiler on a two wheeled frame.

Plate 4.6: The sub-soiler in operation

4.4 Data Collection

The draft as recorded on the dynamometer was conveyed to the datalogger via a signal. The datalogger was connected to a laptop which was installed with a software that could decode the signal and display the data on the interface of the laptop. This was saved for further interpretation.

Plate 4.7: Monitoring and recording draft power on a digital datalogger.

4.4 Data analysis

4.4.1 Analysis of Variance (ANOVA)

The data on rake angle were entered into excel and checked to clean errors. The clean data was transferred into Genstat spreadsheet in Genstat Discovery 4 (Payne, 2009). Effects of rake angle on draft power 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). The recorded draft was divided by the subsoiler's effective surface area which penetrated into the ground for that given operation to obtain specific draft. Results were presented through tabulation and graphic display of key significant findings.

4.4.2 Regression Analysis

Coefficient of determination, denoted R^2 or r^2 and pronounced R squared, is a number that indicates how well data fit a statistical model – sometimes simply a line or curve (Saville, 2003). It is a statistic used in the context of statistical models whose main purpose is either the prediction of future outcomes or the testing of hypotheses, on the basis of other related information. It provides a measure of how well observed outcomes are replicated by the model, as the proportion of total variation of outcomes explained by the model.

The Coefficient of determination, R^2 is calculated using equation Y

$$R^2 = \frac{SSR}{SST} = \frac{Sum\ of\ squares\ explained\ by\ regression}{Total\ sum\ of\ squares} \qquad [4.5]$$

Where:

$$\boldsymbol{SSR} = \sum (\hat{\boldsymbol{y}} - \bar{\boldsymbol{y}})^2 \qquad [4.6]$$

$$SST = \sum (y - \bar{y})^2 \qquad [4.7]$$

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.

5.0 RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The results listed here-in are for the physical soil characteristics of the experimental field, draft power requirement in relation to tillage speeds and depth, modeling for best fit and optimizing specific draft force requirement with rake angles. The physical soil characteristics determined prior to the experiment were penetration resistance, gravitational soil moisture content, dry and wet bulk soil density and classification of the soil based on its texture.

5.2 SOIL PHYSICAL ATTRIBUTES

The overall soil texture across the three depths as deduced from the texture triangle was clay loam (Table 5.1). The 200 and 300 mm soil layers however had a clay texture.

Table 5.1: Soil Texture Analysis

Depth (mm)	Proportions of soil separates (%)			Soil textural class
	Sand	Clay	Loam	
100	46	32	23	Clay loam
200	41	41	18	Clay
300	38	45	17	Clay
Mean	41	39	19	Clay loam

$^{\alpha}$Each value is a mean of three replications

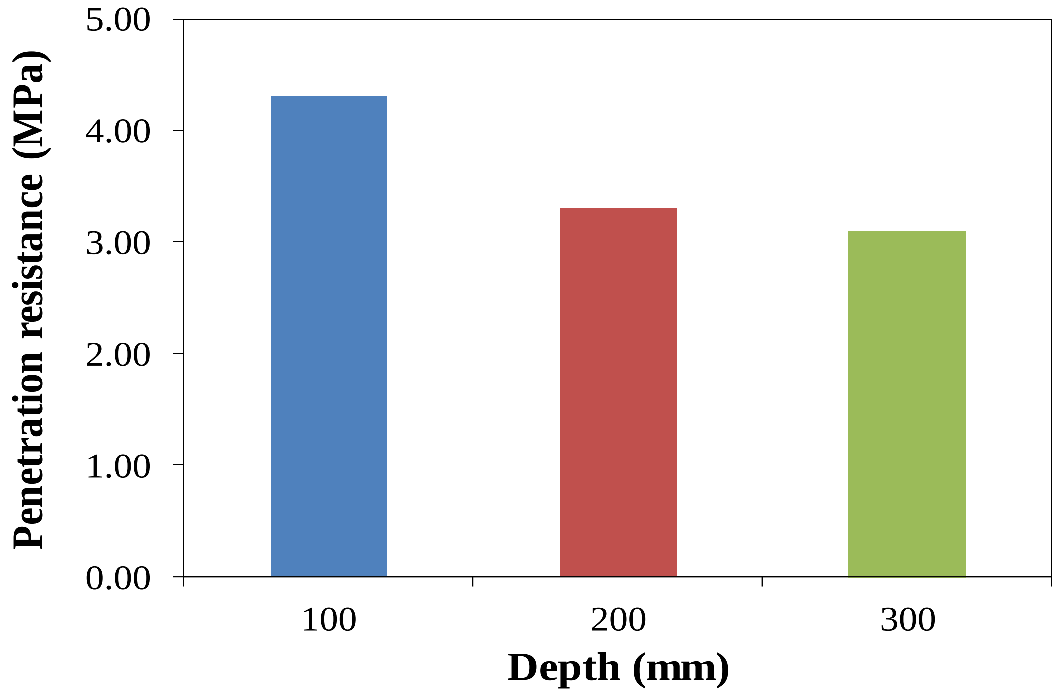


Figure 5.1: Soil Penetration Resistance for Experimental Site

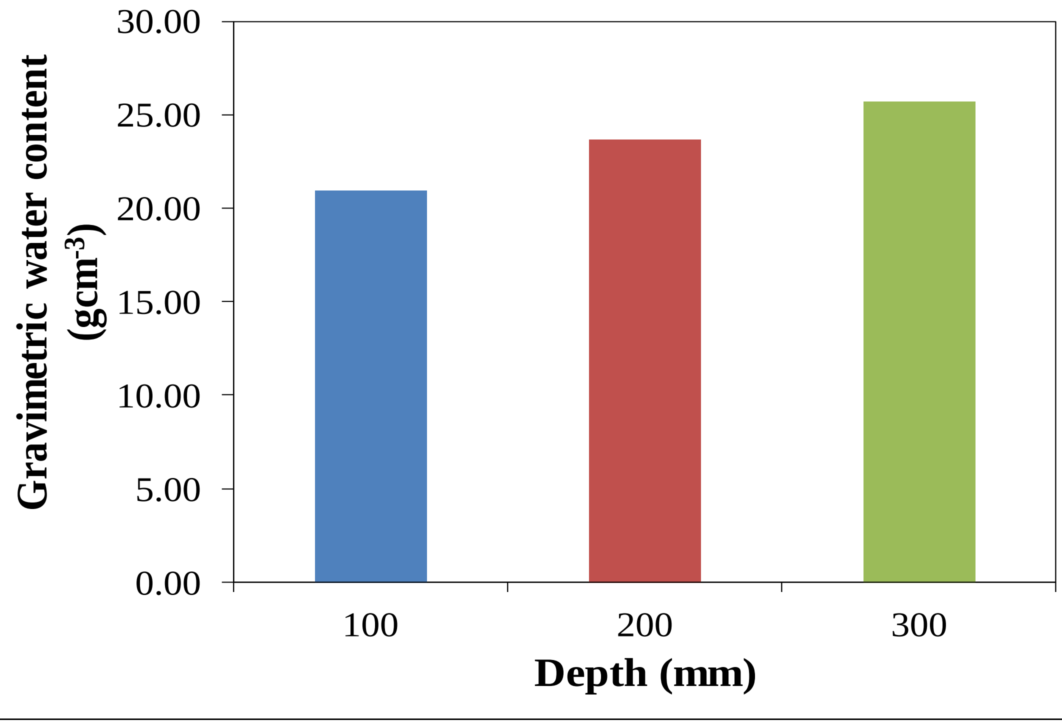


Figure 5.2: Gravimetric Water Content for Experimental Site

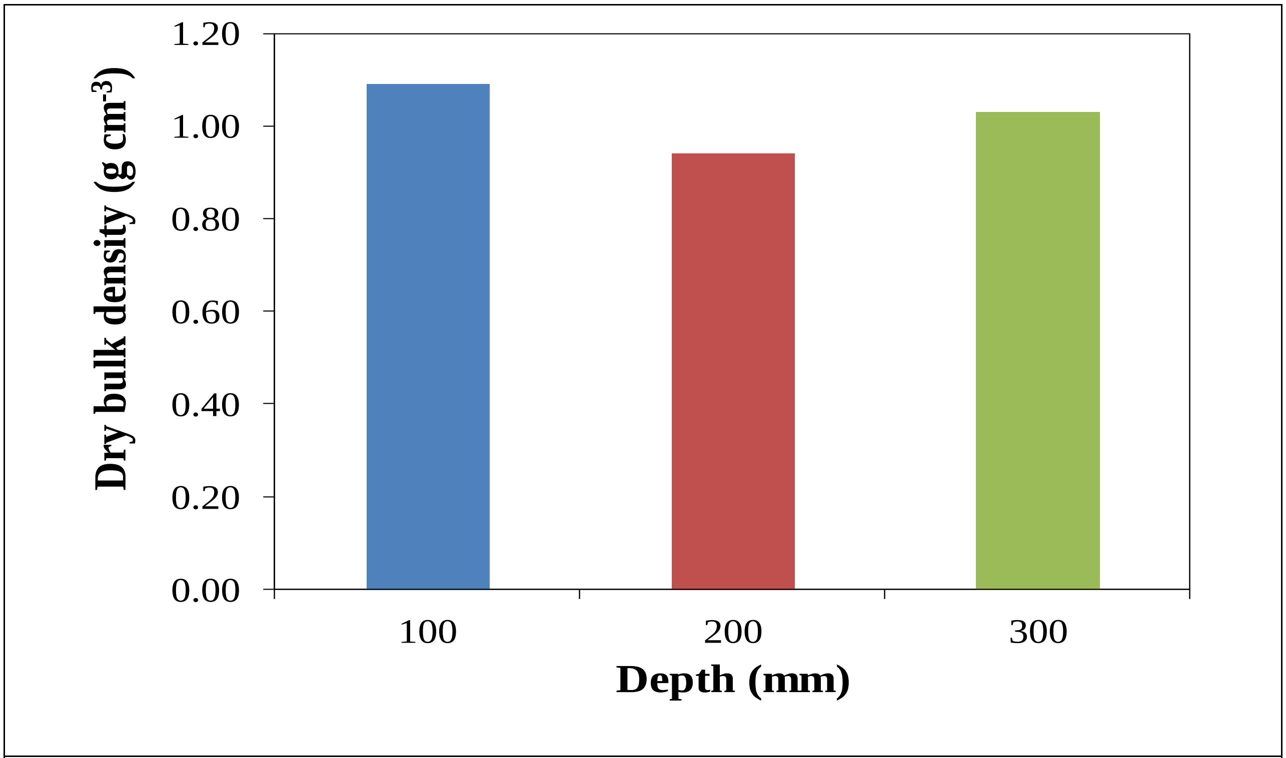


Figure 5.3: Dry Bulk Density for Experimental Site

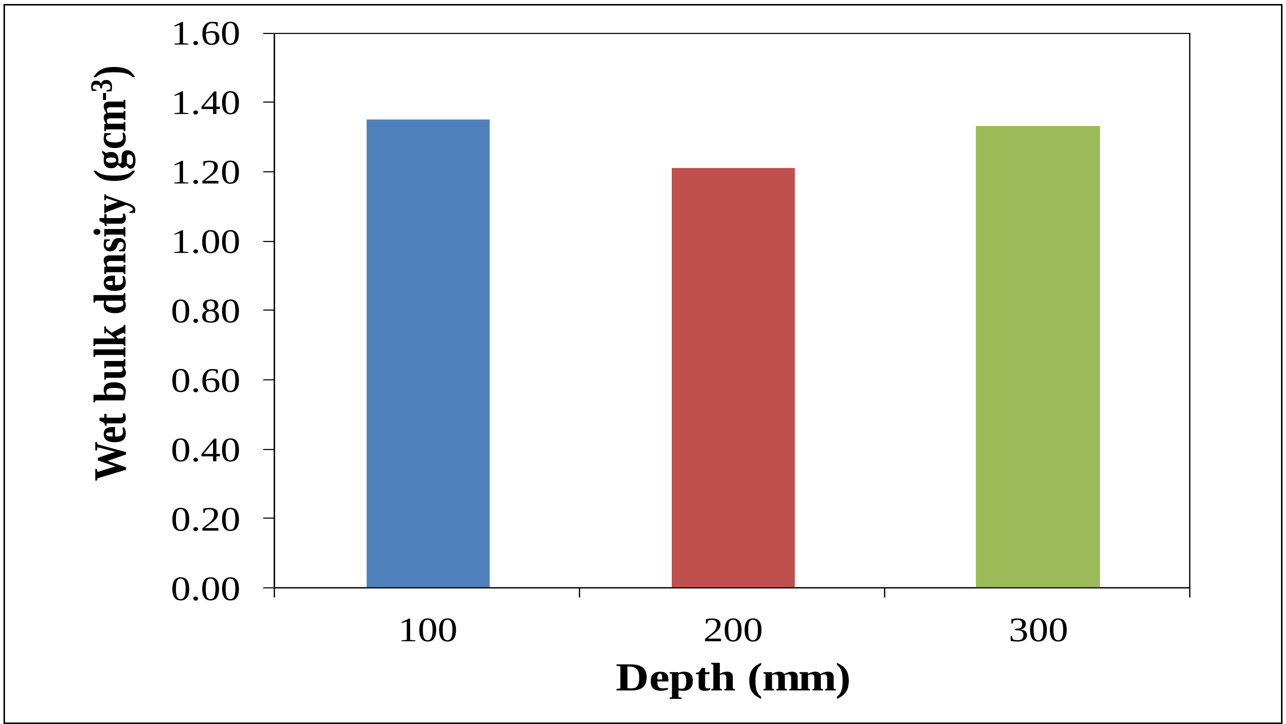


Figure 5.4: Wet Bulk Density for Experimental Site

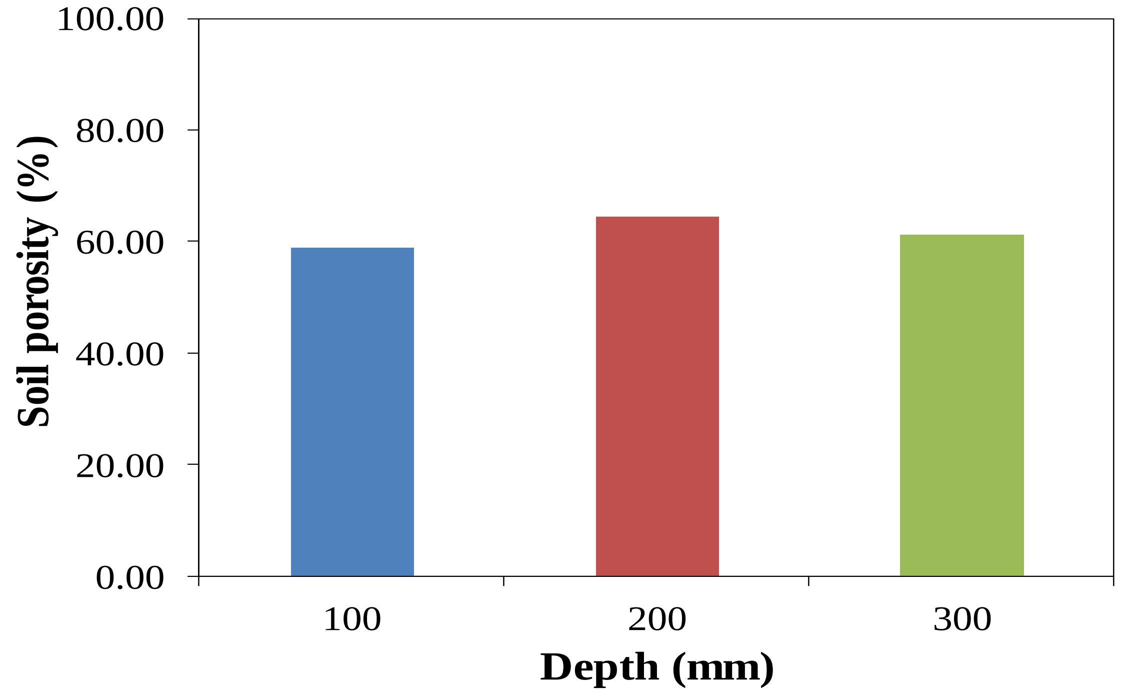


Figure 5.5: Soil Porosity for Experimental Site

The penetration resistance of the experimental field decreased by 23% between the 100 and 200 mm soil depths (Figure 5.1). The 200 and 300 mm soil depths had similar levels of penetration resistance which were 3.3 and 3.1 MPa respectively.

The gravimetric soil water content was not uniform (Figure 5.2). The soil moisture content for the soil surface (100 mm depth) was 20.98 gcm^{-3} and increased gradually by 13% for the 200 mm depth and 22% for the 300 mm depth. Soil columns tend to be drier at the top because of evaporation from the surface (Gong *et al*., 2003).

The average dry and wet bulk densities of the soil were 1.0 gcm^{-3} and 1.35 gcm^{-3} respectively across the depth range (Figure 5.3 and 5.4). The dry bulk density for this soil is within the normal range of bulk densities for clay which is 1.0 to 1.6 g/cm^3 (Chaudhari *et al*., 2013). The calculated soil porosity was highest (65%) for the 200 mm depth (Figure 5.5). The 100 mm and 300 mm depths had similar soil porosity that was 59 and 61% respectively.

Soils are composed of solids (minerals and organic matter), and pores which hold air and water. The "ideal" soil would hold sufficient air and water in the pores to meet the needs of plants with enough pore space for easy root penetration, while the mineral soil particles would provide physical support and plant essential nutrients. Soil bulk density is a basic soil property influenced by some soil physical and chemical properties. Bulk density is influenced by the amount of organic matter in soils, their texture, constituent minerals and porosity. Knowledge of soil bulk density is essential for soil management, and information about it is important in soil compaction as well as in the planning of modern farming techniques, particularly tillage. A normal range of bulk densities for clay is 1.0 to 1.6 mg/m^3 and a normal range for sand is 1.2 to 1.8 mg/m^3 with potential root restriction occurring at ≥ 1.4 mg/m^3 for clay and ≥1.6 mg/m^3 for sand (Chaudhari *et al*., 2013).

5.3 DRAFT POWER REQUIREMENT, TILLAGE SPEED AND TILLAGE DEPTH

The average specific draft force for 1st tillage speed of 0.6 m/s was 45 kNm^{-2}. Between the three tillage depths, the 200 mm depth had the greatest average specific draft force followed by the 300 mm depth (Table 5.2). The average specific draft force decreased as the rake angle increased from 53 kNm^{-2} for 30^0 rake angle to 39 kNm^{-2} for the 70^0 rake angle.

Table 5.2: Specific draft force (kNm-2) for sub-soiling at different rake angles and tillage depths for the 1st tillage speed of 0.6 ms-1

Rake angle (degrees)	Tillage Depth (mm)			Mean
	100	200	300	
30	48	56	54	**53**
40	36	54	58	**49**
50	20	51	53	**41**
60	34	47	41	**41**
70	40	41	36	**39**
Mean	**36**	**50**	**48**	**45**

The average specific draft force for 2nd tillage speed of 1.2 m/s was 48 kNm^{-2}. As the case for the 1st tillage speed, the 200 mm depth had the greatest average specific draft force and the average specific draft force decreased as the rake angle increased from 57 kNm^{-2} for 30^0 rake angle to 42 kNm^{-2} for the 70^0 rake angle (Table 5.3). The specific draft force in this experiment is within the range reported by Kepner *et al*. (1982).

Table 5.3: Specific draft force (kNm-2) for sub-soiling at different rake angles and tillage depths for the 2nd tillage speed of 1.2 ms-1

Rake angle (degrees)	Tillage Depth (mm)			Mean
	100 mm	200 mm	300 mm	
30	50	59	61	**57**
40	38	59	57	**51**
50	34	54	47	**45**
60	45	54	40	**46**
70	33	49	43	**42**
Mean	**40**	**55**	**50**	**48**

From the ANOVA results (Table 5.4), the difference in draft power between tillage speeds was not significant (P=0.088). Rake angle and tillage depth had significant main (P<0.001) and interactive effects on draft power requirement (P=0.023). The combination of rake angle and tillage depth leads to non-linear effects on draft power requirement. These results are in agreement with the findings reported by Al-Janobi and Al-Suhaibani (1998) who found draft power for tillage to exhibit greater influence from tillage depth as opposed to tillage speed.

Table 5.4: Analysis of variance for angle, speed and depth of tillage on the draft power requirement

Fixed term	Degrees of freedom	F statistic	P Value
Angle	4	8.65	<0.001
Depth	2	17.86	<0.001
Speed	1	2.98	0.088
Angle. Depth	8	2.38	0.023
Angle. Speed	4	0.51	0.726
Depth. Speed	2	0.53	0.588
Angle. Depth. Speed	8	1.07	0.394

For small rake angles ($<40^0$), the specific draft force increased linearly with sub-soiling depth (Figure 5.6) while at greater rake angles ($>40^0$), the specific draft increased initially (0 - 200 mm) followed by a decrease as the sub-soiling depth increased.

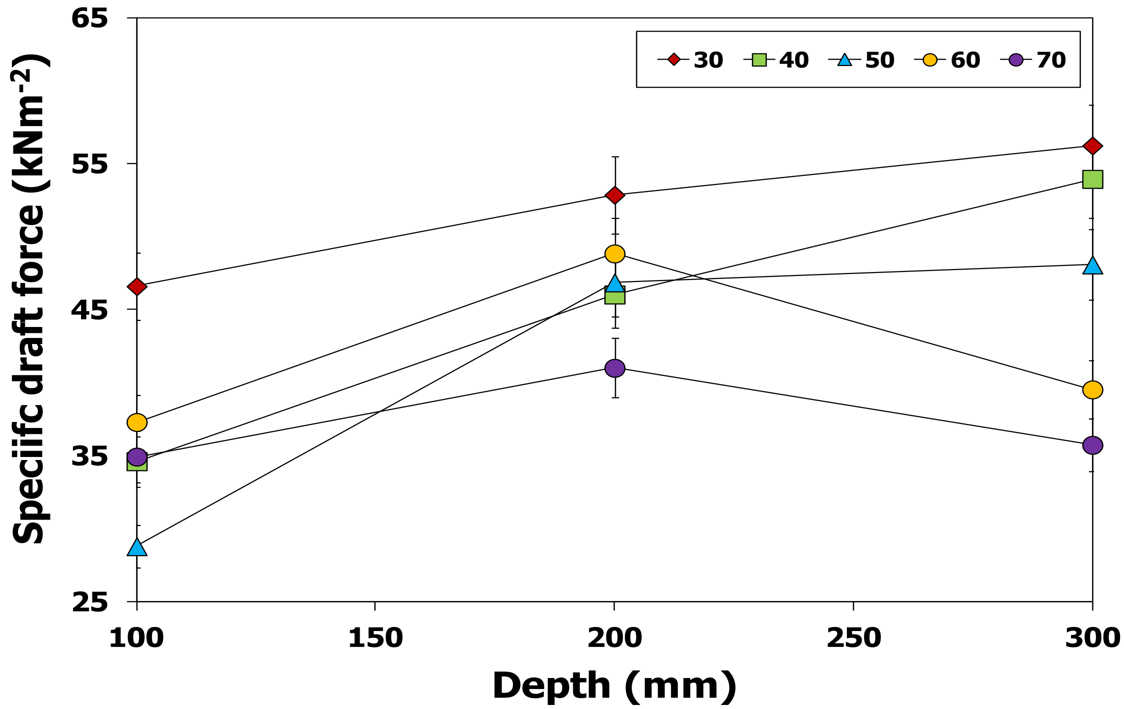


Figure 5.6: The drat force for various sub-soiling depths for different rake angles.

5.4 MODEL FITTING

Multiple regressions were performed on the calculated values of draft power of the sub-soiler using a General Linear Model (GLM) procedure in Genstat SAS (1986). A number of different best-fit unit draft equations were formulated for the draft power for different rake angles at each depth. The general form of the equation used in this analysis was draft power requirement as a function of rake angles at specific tillage depth. The regression equation giving a good fit with a maximum coefficient of regression, R^2 and variables that have significant effect on the draft of all the implements was:

$$\mathbf{P = \alpha_o + \alpha_1 \, x \, R + \alpha_2 \, x \, R^2 + \alpha_3 \, x \, R^3} \qquad \textbf{[5.1]}$$

Where:

P = Draft power

R = Rake angles

$\alpha_{1,2,3}$, are the regression coefficients

The best-fit regression coefficients of powers of rake angle for different tillage depths are given in Table 5.5 and 5.6. The variables which had probability, $P < 0.05$ were considered for determining any significant effect of rake angle on the draft power requirement for the sub-soiler tested. The rake angle had no effect on the draft power requirement at the 100-200 mm tillage depths (Table 5.5 and Appendix III and IV).

There was significant linear, square and quadratic effects of the rake angle on the draft power requirement at the 300 mm tillage depth for the sub-soiler (Table 5.5 and Appendix V). Soil reactions to tillage tools is influenced by soil conditions and tool geometry. Sub-soilers shatter soil at an angle from a point just above the tine tip to the soil surface (angle of crescent failure).

Table 5.5: Best-fit regression data for the sub-soiler

Depth (mm)	Symbol	Value	Probability (P)	R^2
100				
	α_o	50	0.022	0.253^{NS}
	α_i	0.22	0.387	
200				
	α_o	61	0.002	0.586^{NS}
	α_i	-0.22	0.132	
300				
	α_o	83.043	0.028	0.956*
	α_i	-1.1764	0.078	
	α_{ii}	0.0082	0.045	

The angle of crescent failure varies, but it generally ranges from 20° to 45° from vertical (Koohestani and Gregory, 1985; Gregory and M'Hedhbi, 1988; and Tong and Moayad, 2006). Below a critical depth, soil only flows forward and sideways (lateral failure) around the point, compacting soil in the area of the point without increasing soil disturbance (Spoor and Godwin, 1978). The critical depth is a function of Subsoiler point geometry. Tines of similar width and rake angle have about the same critical depth. The critical depth with a narrow Subsoiler point is typically about 30 cm (12 in.) (Cooper, 1971), but this depth is likely deeper in clay than sandy loam soils (Owen, 1988). In a given soil, the critical depth is deeper in friable than in wet or plastic soil conditions (Spoor and Godwin, 1978).

The effect of rake angle and tillage depth on the draft power requirement for sub-soiling presented in a regression equation form allows prediction of the draft requirement for the Subsoiler on Nitisols within the ranges of rake angle and tillage depths used. The least square fit with an R^2 of 0.956 indicates that the model overestimated draft requirement by approximately 4.4%. This shows that draft power for sub-soiling can be predicted with some success for the sub-soiler tested. Subsoiler draft has been shown to have a positive linear function to depth (ASAE, 1994; Garner and Wolf, 1981; Upadhyaya *et al*., 1995) and a quadratic function with respect to speed (Owen, 1989; Upadhyaya *et al*., 1995).

Table 5.6: Regression for the 300 mm depth

Regression statistics	
Regression statistic	**Statistic value**
Multiple R	0.999924
R Square	0.956478
Adjusted R Square	0.005284
Standard Error	0.020971
Observations	5

Analysis of variance

Source	**df**	**SS**	**MSS**	**F_{ratio}**	**P-value**
Regression	1	2.882717	0.960906	2185.016	0.015725
Residual	3	0.00044	0.00044		
Total	4	2.883157			

Regression coefficients

Coefficient	**Coefficient value**	**Standard Error**	**t-Statistic**	**P-value**
Intercept	83.053	0.195842	22.50806	0.028265
X Variable 1	1.1764	0.008908	8.085175	0.078341
X Variable 2	0.0082	8.74E-05	-14.0218	0.045326

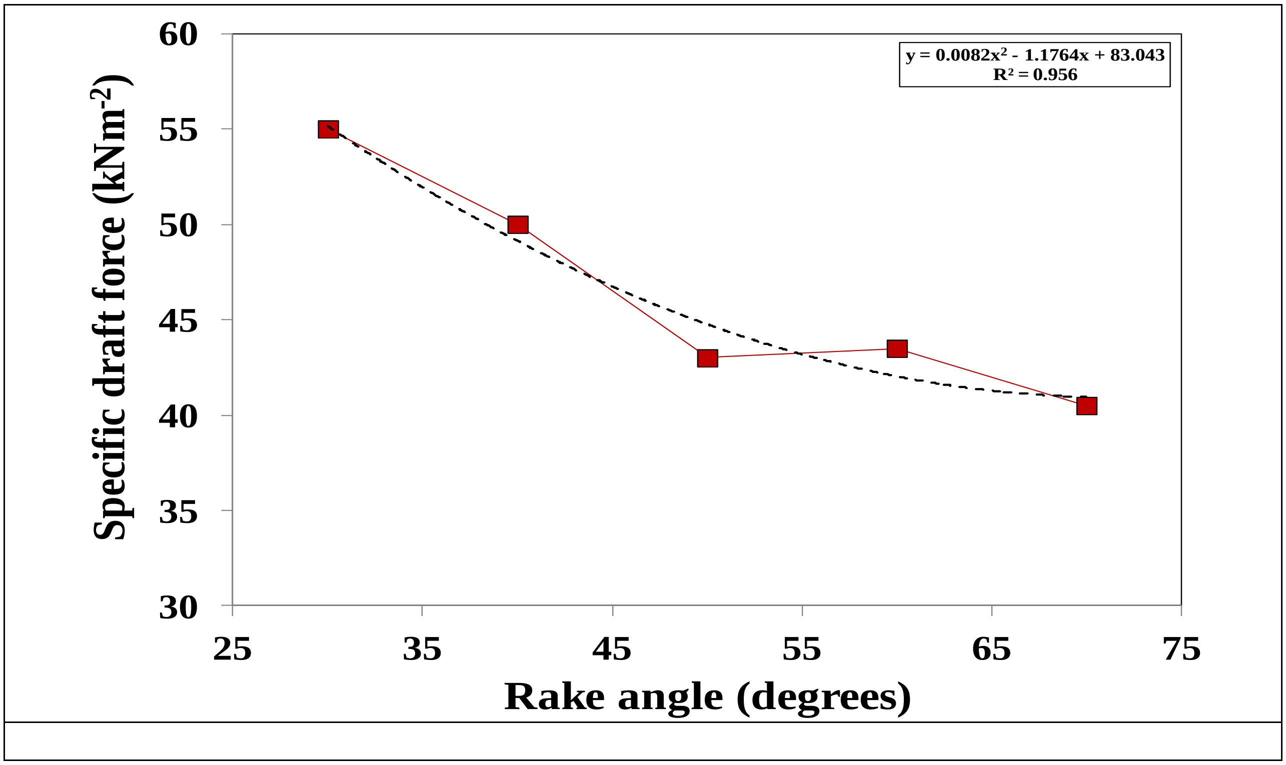


Figure 5.7: The 2nd order regression for different rake angles in the 300mm sub-soiling depth

The best fit model graph from the 2nd order regression generated equation 5.2

$$y = 0.0082x^2 - 1.1764x + 83.043 \qquad [5.2]$$

For optimization of the operational rake angle, equation 5.2 was differentiated and equated to zero.

Therefore differentiating equation 5.2

$$\frac{d(0.0082x^2 - 1.1764x + 83.043}{dx} = 0 \qquad [5.3]$$

$0.0164x - 1.1764 = 0$

$$x = \frac{1.1764}{0.0164}$$

$x = 71.73^0 \approx 72^0$

Substituting 71.73^0 for x in equation 5.2

y = 0.0082 (71.73)2 – 1.1764 (71.73) + 83.043

= 42.19 – 84.38 + 83.043

= 40.85kNm^{-2}

This implies that the optimum rake angle is 72^0 for a minimum specific draft force of 41kNm^{-2} (Figure 5.8). 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 (1 Tropical Livestock Unit) can generate a draft force of 60 kN adequate for the sub-soiling at the optimal rake angle in clay soils as established in this study

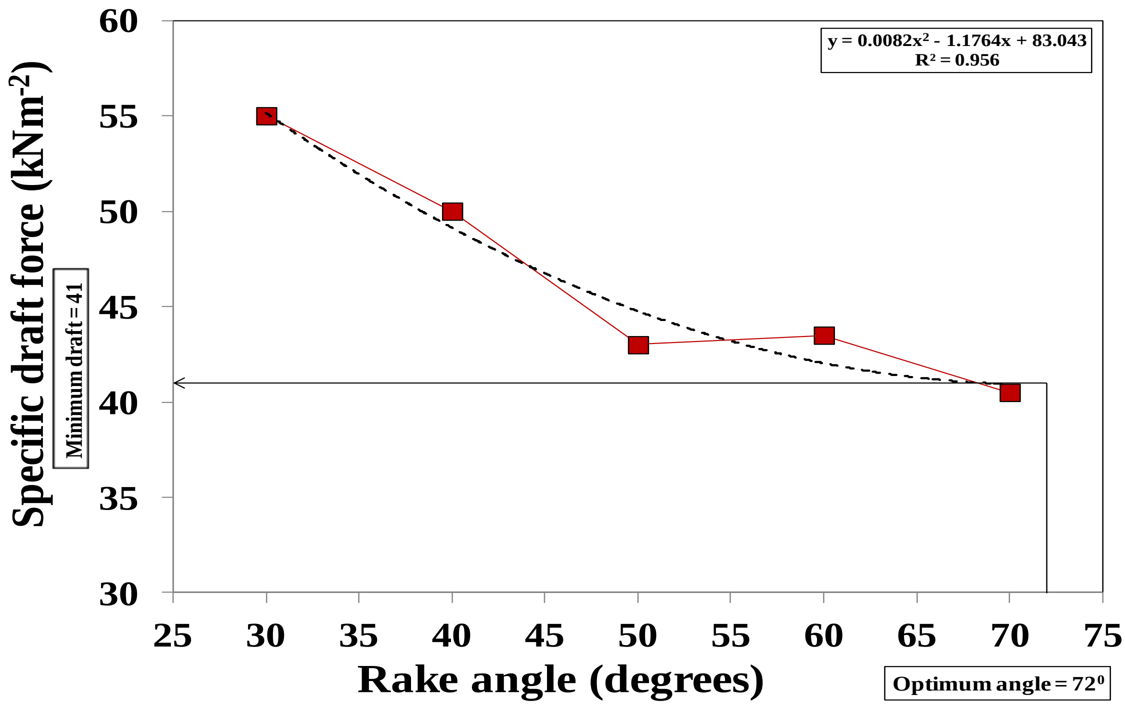


Figure 5.8: Optimum Rake Angle for Minimum Specific Draft Force

5.5 SUMMARY OF FINDINGS AND CONTRIBUTION

The average specific draft force for the 1st tillage speed of 0.6 m/s was 45 kNm^{-2}. Between the three tillage depths, the 200 mm depth had the greatest average specific draft force followed by the 300 mm depth (Table 5.2). The average specific draft force decreased as the rake angle increased from 53 kNm^{-2} for 30^0 rake angle to 39 kNm^{-2} for the 70^0 rake angle. The average specific draft force for the 2st tillage speed of 1.2 m/s was 48 kNm^{-2}. As the case for the 1st tillage speed, the 200 mm depth had the greatest average specific draft force and the average specific draft force decreased as the rake angle increased from 57 kNm^{-2} for 30^0 rake angle to 42 kNm^{-2} for the 70^0 rake angle (Table 5.3). This implies that the hard pan was at a tillage depth of 200 mm.

The ANOVA results (Table 5.4), Showed that the difference in specific draft force between tillage speeds was not significant (P=0.088). Rake angle and tillage depth had significant main (P<0.001) and interactive effects on draft power requirement (P=0.023). The difference between the two speeds chosen for this study was not significant. This resulted into the specific draft forces generated for both speeds being almost the same contrary to scientific theories. The best-fit regression coefficients of powers of rake angles for different tillage depths were calculated. There was a significant linear, square and quadratic effect of the rake angle on the specific draft force requirement at the 300 mm tillage depth for the Subsoiler (Table 5.5 and Appendix V). The best-fit model graph from the 2nd order regression generated a quadratic equation which was differentiated for optimization. The results gave an optimum rake angle of 72^0 for a minimum specific draft force requirement of $41kNm^{-3}$.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Field study was conducted to determine the effects of speed, rake angle and tillage depth on the draft requirement of a sub-soiler. The tillage speeds tested had no effect on the draft power requirement for sub-soiling. These are the minimum and maximum speeds a draft animal can achieve when drawing a land preparation implement. A significant increase in draft power was observed with an increase in tillage depth while the draft power requirement decreased as the rake angle increased. There was significant interaction ($P<0.05$) between tillage depth and rake angle on the draft power requirement. A draft equation for the sub-soiler was developed based on rake angle and tillage depth. Draft requirement for the sub-soiler was closely predicted with a 2^{nd} order regression equation including the rake angle at the 300 mm tillage depth with reasonable accuracy. Depths below 300 mm did not show any significant change in the specific draft force as the rake angles were varied. This implies the critical depth for this particular experimental field was at 300 mm depth. Subsoiling beyond this depth would result in the Subsoiler point compacting and smearing the soil along the channel created by the point instead of cracking and lifting it up. The optimum rake angle was found to be 72^0 with a minimum specific draft force requirement of $41kNm^{-2}$ for subsoiling in clay soils. Therefore, two oxen of average weight 250 kg (1 Tropical Livestock Unit) can generate a draft force of 60 kN adequate for the sub-soiling at the optimal rake angle in clay soils as established in this study.

6.2 RECOMMENDATION

The following recommendations can be made for efficient and effective sub-soiling tillage operations:

(1) The recommended sub-soiling depth for clay soils if animal draft is used should be at least 300 mm.

(2) Animal drawn sub-soilers in Kenya are currently produced with a fixed rake angle of 50^{o} regardless of soil type. For clay soils, there is need to increase the rake angle to 72^{o} in order to take advantage of the possible reduction in draft power requirement.

The following recommendations can be made for further research:

(1) Further studies should be conducted for determination of draft power requirement for sub-soiling in Nitisols at greater speeds as the rake angle is varied so as to utilize tractor power as the prime mover.

(2) Further studies should be conducted for determination of draft power requirement for sub-soiling in other soil types.

7. REFERENCES

Al-Suhaibani. (2010). Effect of Plowing Depth of Tillage and Forward Speed on the Performance of a Medium Size Chisel Plow Operating in a Sandy Soil. *American Journal of Agricultural and Biological Sciences*. doi:10.3844/ajabssp.2010.247.255

Amanullah, M. M. Srikanth, M. & Muthukrishnan, P. (2010). Soil compaction and deep tillage - a review. *Agricultural Reviews*, *31*(2), 105–112. Retrieved from <Go to ISI>://CABI:20103271872

American Society of Agricultural and Biological Engineers. (2011). ASAE D497.7 MAR2011 Agricultural Machinery Management Data. *Test*.

Anon. (1992). Tools for Agriculture. A guide to appropriate equipment for small holder farmers. CTA publication. p. 238.

Asota C.O. (1996). Animal Draught Technology: A viable mechanization alternative to tractorisation in small farms. Proceedings of the training programme held at IAR, Zaria, Nigeria, 18th September - 14th October, 1995 under the sponsorship of the Commonwealth Secretariat, UK. pp. 26-47.

Barwell, I. and M. Ayre. (1982). The harnessing of draft animals. Intermediate Technology Publication.

Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use and Management*, *25*(December), 335–345. doi:10.1111/j.1475-2743.2009.00236.x

Betker J.R. and Kutzbach H.D. (1989). The working performance of animal-drawn implements for soil tillage in Western Africa. Agricultural Engineering, 3: 1517–1522.

Biamah, E.K. Rockström, J. and Okwach, G.E. (2000): Conservation Tillage for Dryland farming: Technological options and experiences in Eastern and Southern Africa.

Blanco, H. and Lal, R. (2010). *Soil and Water Conservation*. *Principles of Soil Conservation and Management*. Springer Netherlands.

Brassington T.J.M. (1987). Re-examination of the plough. Agricultural Engineer, 5: 53–57.

Celik, A. and Raper, R. L. (2012). Design and evaluation of ground-driven rotary subsoilers. *Soil and Tillage Research*, *124*, 203–210.

Cetin, H. Fener, M. Söylemez, M. and Günaydin, O. (2007). Soil structure changes during compaction of a cohesive soil. *Engineering Geology*, *92*(1-2), 38–48.

Chartier, S. and Cousineau, D. (2011). Computing Mixed-Design (Split-Plot) ANOVA. *The Mathematica Journal*. doi:10.3888/tmj.13-17

Chaudhari, P.R. Ahire, D.U. Ahire, V.D. Chkravarty, M. and Maity, S. (2013). Soil bulk density as related to soil texture, organic matter content and available total nutrients of combatore soils. *International Journal of Scientific and Research Publications*, 3(2), 1 – 8.

Chaudhuri, D. (2001). Performance Evaluation of Various Types of Furrow Openers on Seed Drills-a Review. *Journal of Agricultural Engineering Research*, *79*(2), 125–137. doi:10.1006/jaer.2000.0688

Cohron, G. T. (1963). Soil Sheargraph. Agric. Engng., vol. 44, pp. 554-556.

Collins, B. A. and Fowler, D. B. (1996). Effect of soil characteristics, seeding depth, operating speed, and opener design on draft force during direct seeding. *Soil and Tillage Research*, *39*(3-4), 199–211.

CTIC. (2005). Conservation Technology Information Center.

Daraghmeh, O. A. Jensen, J. R. and Petersen, C. T. (2009). Soil structure stability under conventional and reduced tillage in a sandy loam. *Geoderma*, *150*(1-2), 64–71.

Dardanelli, J. L. Bachmeier, O. A. Sereno, R. and Gil, R. (1997). Rooting depth and soil water extraction patterns of different crops in a silty loam haplustoll. *Field Crops Research*, *54*(1), 29–38.

Davies, P. (1985). Influence of organic matter content, moisture status and time after reworking on soil shear strength. *Journal of Soil Science*, *36*(2), 299–306.

Dexter, A. R. Czyż, E. A. and Gaţe, O. P. (2007). A method for prediction of soil penetration resistance. *Soil and Tillage Research*. doi:10.1016/j.still.2006.05.011

Ditzler, C. A. and Tugel, A. J. (2002). Soil quality field tools: Experiences of USDA-NCRS Soil Quality Institute. In *Agronomy Journal* (Vol. 94, pp. 33–38).

Fan, C. C. and Su, C. F. (2008). Role of roots in the shear strength of root-reinforced soils with high moisture content. *Ecological Engineering*, *33*(2), 157–166.

Fielke, J. M. (1996). Interactions of the Cutting Edge of Tillage Implements with Soil. *Journal of Agricultural Engineering Research*, *63*(1), 61–71. doi:10.1006/jaer.1996.0008

Gardner, W. H. (1986). Water content. Methods of soil analysis, Part 1. Agronomy, vol. 9, pp. 493-544.

Ghosh, P. K. Mohanty, M. Bandyopadhyay, K. K. Painuli, D. K. and Misra, A. K. (2006). Growth, competition, yield advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India: I. Effect of subsoiling. *Field Crops Research*, *96*(1), 80–89.

Giller, K.E. Witter, E. Corbeels, M. and Tittonell, P. (2009), Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Research 114 (1), pp. 23-24.

Gitau, A. N. Kasisira L.L. and Z.M. Mganilwa. (2012). Mechanization status in the Lake Victoria Basin of East Africa. AJAE 1(5):160-164 (2010).

Godwin, R. J. (2007). A review of the effect of implement geometry on soil failure and implement forces. *Soil and Tillage Research*.

Godwin, R. J. and O'Dogherty, M. J. (2007). Integrated soil tillage force prediction models. *Journal of Terramechanics*, *44*(1), 3–14.

Gong, Y. Cao, Q. and Sun, Z. (2003). The effects of soil bulk density, clay content and temperatute on soil water content measurement using time-domain reflectometry. *Hydrol. Process.* 17, 3601 - 3614

Günay, M. Korkut, I. Aslan, E. and Şeker, U. (2005). Experimental investigation of the effect of cutting tool rake angle on main cutting force. *Journal of Materials Processing Technology*, *166*(1), 44–49.

Hamza, M. A. and Anderson, W. K. (2005). Soil compaction in cropping systems. *Soil and Tillage Research*. doi:10.1016/j.still.2004.08.009

Harrigan. T. and Roosenberg, R. (2002). Estimating tillage draft. Tillers International, 10515 E. OP Ave., Scotts MI 49088 TechGuide-2G10. Sharing our Rural Heritage with the World...for a more Peaceful Earth.

Herrick, J. E. and Jones, T. L. (2002). A dynamic cone penetrometer for measuring soil penetration resistance. *Soil Science Society of America Journal*. doi:10.2136/sssaj2002.1320

Horn, R. Taubner, H. Wuttke, M. and Baumgartl, T. (1994). Soil physical properties related to soil structure. *Soil and Tillage Research*. doi:10.1016/0167-1987(94)90005-1

Huat, B. B. (2006). Deformation and Shear Strength Characteristics of Some Tropical Peat and Organic Soils. *Pertanika J. Sci & Technol.*, *14*(1 & 2), 61–74.

Huho, J. M. Ngaira, J. K. W. & Ogindo, H. O. (2009). Climate Change and Pastoral Economy in Kenya: A Blinking Future. *ACTA GEOLOGICA SINICA-ENGLISH EDITION*, *83*(5), 1017–1023.

Inns F.M. (1990). The mechanics of animal-draught cultivation implements. The Agricultural Engineer, 45: 13–17.

Jin, H. Hongwen, L. Xiaoyan, W. McHugh, A. D. Wenying, L. Huanwen, G. and Kuhn, N. J. (2007). The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. *Soil and Tillage Research*, *94*(2), 493–502.

Johansen, C. Haque, M. E. Bell, R. W. Thierfelder, C. and Esdaile, R. J. (2012). Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. *Field Crops Research*, *132*, 18–32.

Kassam, A. Friedrich, T. Shaxson, F. Pretty, J. (2009). The spread of Conservation Agriculture: Justification, sustainability and uptake. International Journal of Agricultural Sustainability 7 (4), pp. 292–320.

Kaumbutho, P. and Kienzle, J. eds. (2007). Conservation agriculture as practised in Kenya: two case studies. Nairobi. African Conservation Tillage Network, Centre de Coopération Internationale de

Kepner R.A. Bainer R. Bagner E.L. (1982). Principals of Farm Machinery. Westport, CT, AVI Publishers.

Kushwaha, R. L. and Linke, C. (1996). Draft-speed relationship of simple tillage tools at high operating speeds. *Soil and Tillage Research, 39*(1-2), 61–73.

Lampurlanés, J. and Cantero-Martínez, C. (2003). Soil Bulk Density and Penetration Resistance under Different Tillage and Crop Management Systems and Their Relationship with Barley Root Growth. *Agronomy Journal*. doi:10.2134/agronj2003.0526

Licht, M. A. & Al-Kaisi, M. (2005). Strip-tillage effect on seedbed soil temperature and other soil physical properties. *Soil and Tillage Research*, *80*(1-2), 233–249.

Loukanov, I.A. Uziak, J. Michálek, J. (2005). Draught requirements of enamel coated animal drawn mouldboard plough. Res. Agr. Eng., 51, 2005 (2): 56–62.

Luding, S. (2008). Cohesive, frictional powders: contact models for tension. *Granular Matter*. doi:10.1007/s10035-008-0099-x

Máthé, L. Pillinger, G. and Kiss, P. (2010). Effects of Varying Moisture Content and Settlement of Internal Friction, Load Capacity and Cohesion in Loam Soil. In *FISITA Student Congress 2010*.

Maurice, J. (2013). New goals in sight to reduce poverty and hunger. *The Lancet*.

Mazvimavi, K. and S. Twomlow. (2009). Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households in Zimbabwe. Agric. Syst. 101, 20-29.

McKyes, E. and Maswaure, J. (1997). Effect of design parameters of flat tillage tools on loosening of a clay soil. *Soil and Tillage Research*, *43*(3-4), 195–204.

McMillan, H. K. (2012). Effect of spatial variability and seasonality in soil moisture on drainage thresholds and fluxes in a conceptual hydrological model. *Hydrological Processes*, *26*(18), 2838–2844. doi:10.1002/hyp.9396.

Morris, E. (2007). From horse power to horsepower. *Access*, *30*(Spring), 2–9.

Mortvedt, J. J. (1996). Soil science society of America journal. *Symposium A Quarterly Journal In Modern Foreign Literatures*, *72*(1), 1995–1995. doi:10.2136/sssaj2007.0159

Motavalli, P. P. Anderson, S. H. Pengthamkeerati, P. and Gantzer, C. J. (2003). Use of soil cone penetrometers to detect the effects of compaction and organic amendments in claypan soils. *Soil and Tillage Research*, *74*(2), 103–114.

Mouazen, A. M. and Nemenyi, M. (1999). Tillage tool design by the finite element method: Part 1. Finite element modelling of soil plastic behaviour. *Journal Of Agricultural Engineering Research*, *72*(1), 37–51. doi:10.1006/jaer.1998.0343.

Mrema, G.C and M.J. Mrema. (1993). Draft animal technology and agricultural mechanization in Africa: its potential role and constraints. NAMA Newsletter. 2: 12-33

Munzinger, P. (ed), (1982). Animal traction in Africa. GTZ, Eschborn, Germany. 490p. ISBN 3-88085-133-6.

Nawaz, M. F. Bourrié, G. and Trolard, F. (2012). Soil compaction impact and modelling. A review. *Agronomy for Sustainable Development*. doi:10.1007/s13593-011-0071-8

Noor, M. and Hadi, B. A. (2010). The role of curved-surface envelope Mohr-Coulomb model in governing shallow infiltration induced slope failure. *Electronic Journal of Geotechinical Engineering*, *15*, 1–21.

Okalebo J. R. Gathua K.W. and Woomer P.L. (2002). Loboratory Methods of Soil and Plant Analysis. A working Manual (Second Edition). TSBT - CIAT and SACRED Africa, Nairobi, Kenya.

Onwualu, A. P. and Watts, K. C. (1998). Draught and vertical forces obtained from dynamic soil cutting by plane tillage tools. *Soil and Tillage Research*, *48*(4), 239–253.

Osman K.T. (2014). Physical Deterioration of Soil. In Soil Degradation, Conservation and Remediation, Springer Netherlands.

Payne, R. W. (2009). GenStat. *Wiley Interdisciplinary Reviews: Computational Statistics*, *1*(2), 255–258. doi:10.1002/wics.32

Pingali, P. Bigot. Y. and Binswanger, H. (1987). Agricultural mechanization and the evolution of farming systems in sub-Saharan Africa. World Bank in association with Johns Hopkins Press, Baltimore, Maryland, USA. 216p.

Ran, Q. Su, D. Li, P. and He, Z. (2012). Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion. *Journal of Hydrology*, *424-425*, 99–111.

Raper, R. L. (2007). In-row subsoilers that reduce soil compaction and residue disturbance. *Applied Engineering in Agriculture*, 253–258.

Reeder, R. C. and Wood, R. K. (1993). Five subsoiler designs and their effects on soil properties and crop yields. *American Society of Agricultural Engineers*, *36*(6), 1525–1531.

Rusinamhodzi, L. Corbeels, M. Wijk, M. T. Rufino, M. C. Nyamangara, J. and Giller, K. E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development*. doi:10.1007/s13593-011-0040-2

Sahu, R. K. and Raheman, H. (2006). An approach for draft prediction of combination tillage implements in sandy clay loam soil. *Soil and Tillage Research*, *90*(1-2), 145–155.

Sahu, R. K. and Raheman, H. (2008). A decision support system on matching and field performance prediction of tractor-implement system. *Computers and Electronics in Agriculture*, *60*(1), 76–86.

Salokhe V.M. Shirin A.K.M. (1992). Effect of Enamel Coating on the Performance of Disc Plough. Journal of Agricultural Engineering Research, 53: 71–80.

Saville, D. J. (2003). Basic statistics and the inconsistency of multiple comparison procedures. *Canadian Journal of Experimental Psychology = Revue Canadienne de Psychologie Expérimentale*, *57*(3), 167–75

Shmulevich, I. (2010). State of the art modeling of soil-tillage interaction using discrete element method. *Soil and Tillage Research*, *111*(1), 41–53.

Snijders, T. A. B. (2005). Power and sample size in multilevel modeling. In B. S. Everitt and D. C. Howell (Eds.), *Encyclopedia of Statistics in Behavioral Science* (Vol. 3, pp. 1570–1573). doi:10.1111/j.1365-2966.2004.08479.x

Spoor, G. 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use and Management.22:113-122

Starkey, P. (1986). Draught animal power in Africa: priorities for development, research and liaison. Network Paper 14, Farming Systems Support Project, University of Florida, Gainesville, USA. 40p.

Starkey, P. (1989). Harnessing and Implements for Animal Traction. An animal traction resource book for Africa. GATE publication GTZ, Germany.

Starkey, P. (1992). A worldwide view of animal traction highlighting some key issues in eastern and southern Africa. Proceedings of the 1st workshop of the ATNESA held on 18-23 January, 1992 at Lusaka, Zambia.

Starkey, P. (1994). A world-wide view of animal traction highlighting some key issues in eastern and southern Africa. pp. 66-81 in: Starkey P, Mwenya E and Stares J (eds), Improving animal traction technology. Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands. 490p. 92-9081-127-7.

Stolterman, E. and Pierce, J. (2012). Design Tools in Practice : Studying the Designer-Tool Relationship in Interaction Design. In *Proceedings of the Designing Interactive Systems Conference on - DIS '12* (pp. 25–28). doi:10.1145/2317956.2317961

Temesgen, M. Hoogmoed, W. B. Rockstrom, J. and Savenije, H. H. G. (2009). Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. *Soil and Tillage Research*, *104*(1), 185–191.

Thomas, D.B. Erickson, A. Grunder, M. and Mburu, J.K. (1997): Soil and Water Conservation Manual for Kenya. Pg 5-48

Tong, J. and Moayad, B. Z. (2006). Effects of rake angle of chisel plough on soil cutting factors and power requirements: A computer simulation. *Soil and Tillage Research*, *88*(1-2), 55–64.

Tsegaye, T. and Hill, R. L. (1998). Intensive tillage effects on spatial variability of soil physical properties. *Soil Science*, *163*(2), 143–154.

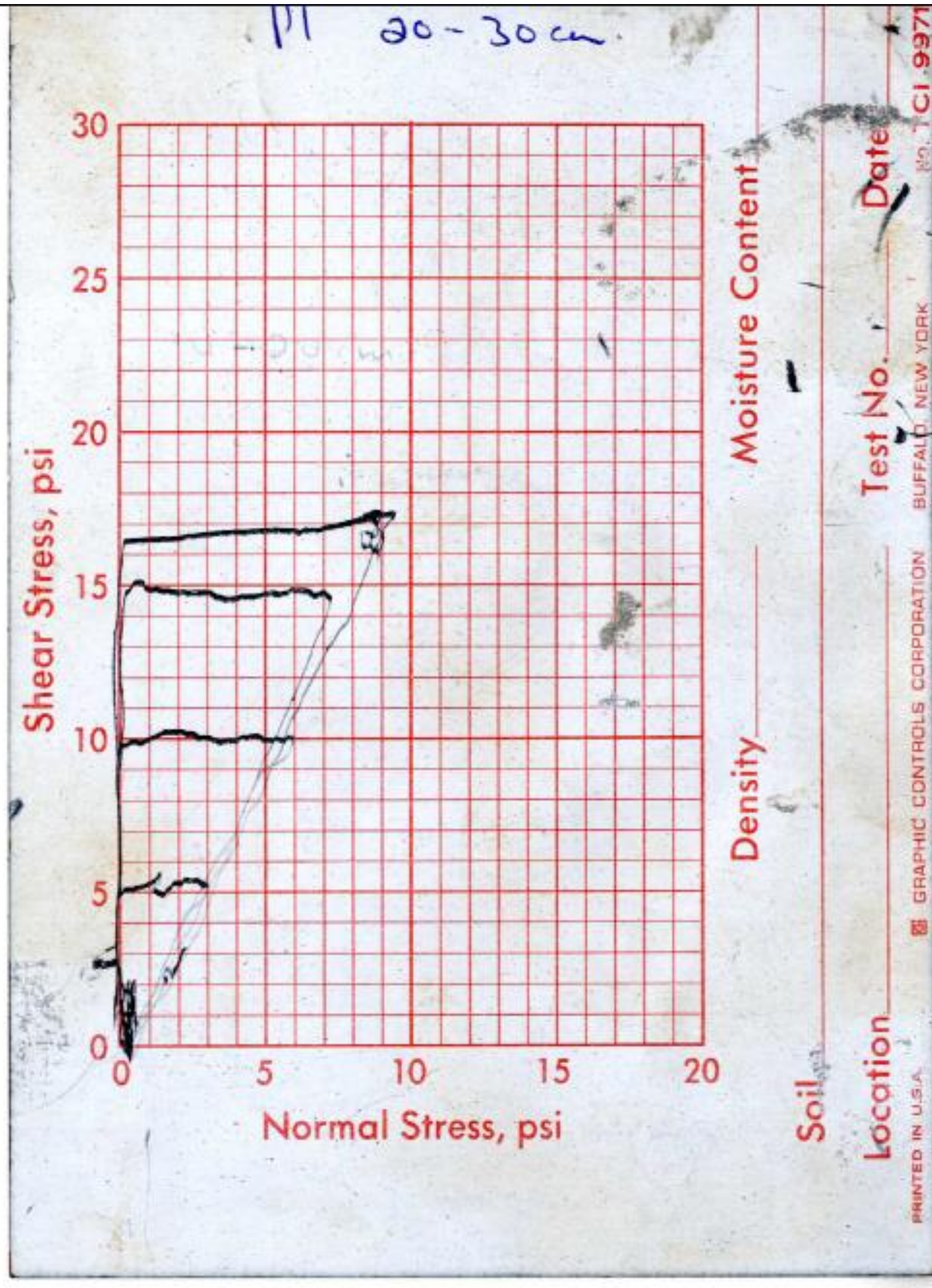
Upadhyaya, S.K. Sakai, K. and Glancey, J. L. (1995). Instrumentation for in-field measurement of soil crust strength. Trans. ASAE vol. 38, no. 1, pp. 39-44.

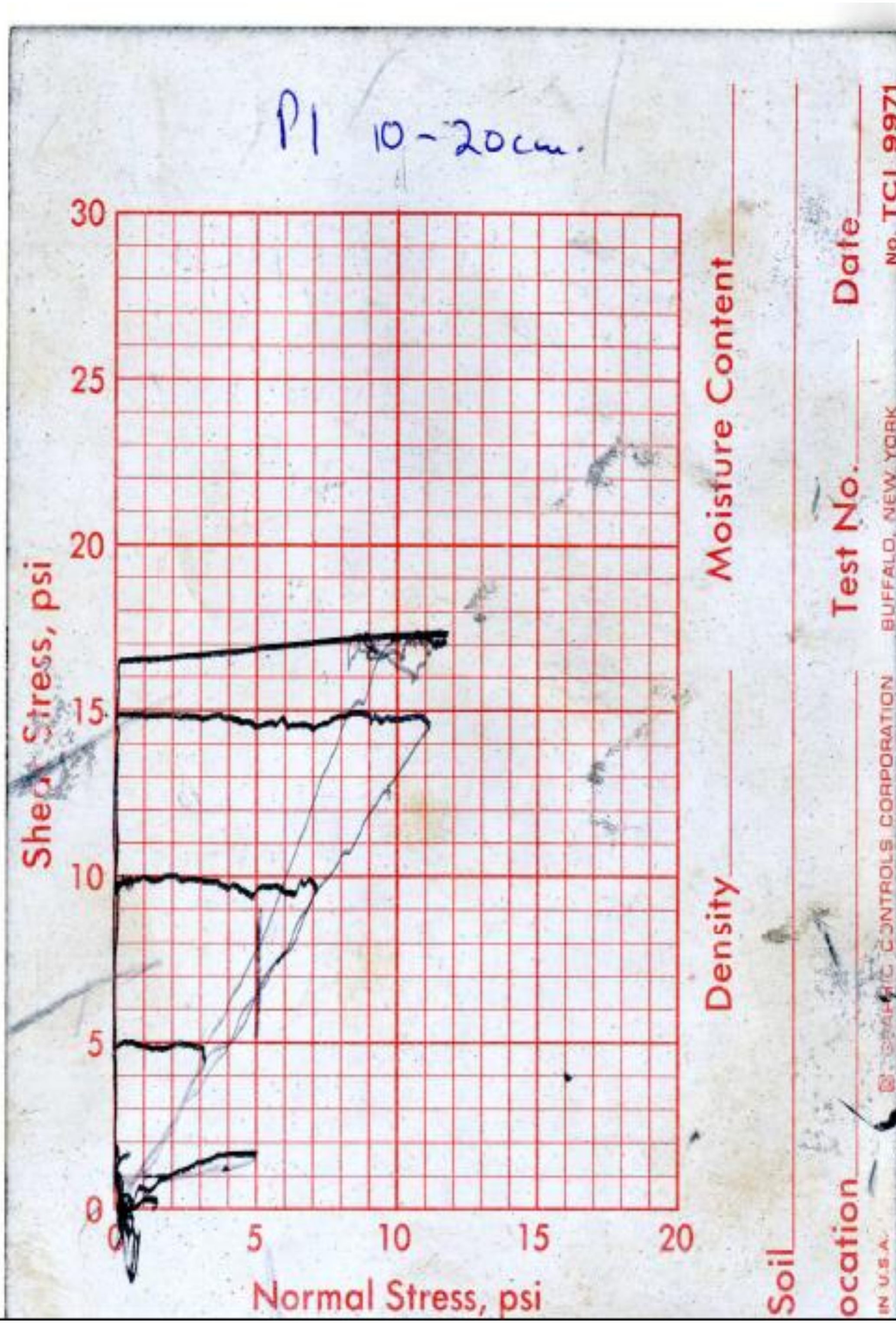
Zhang, B. Zhao, Q. G. Horn, R. and Baumgartl, T. (2001). Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and Tillage Research*, *59*(3-4), 97–106.

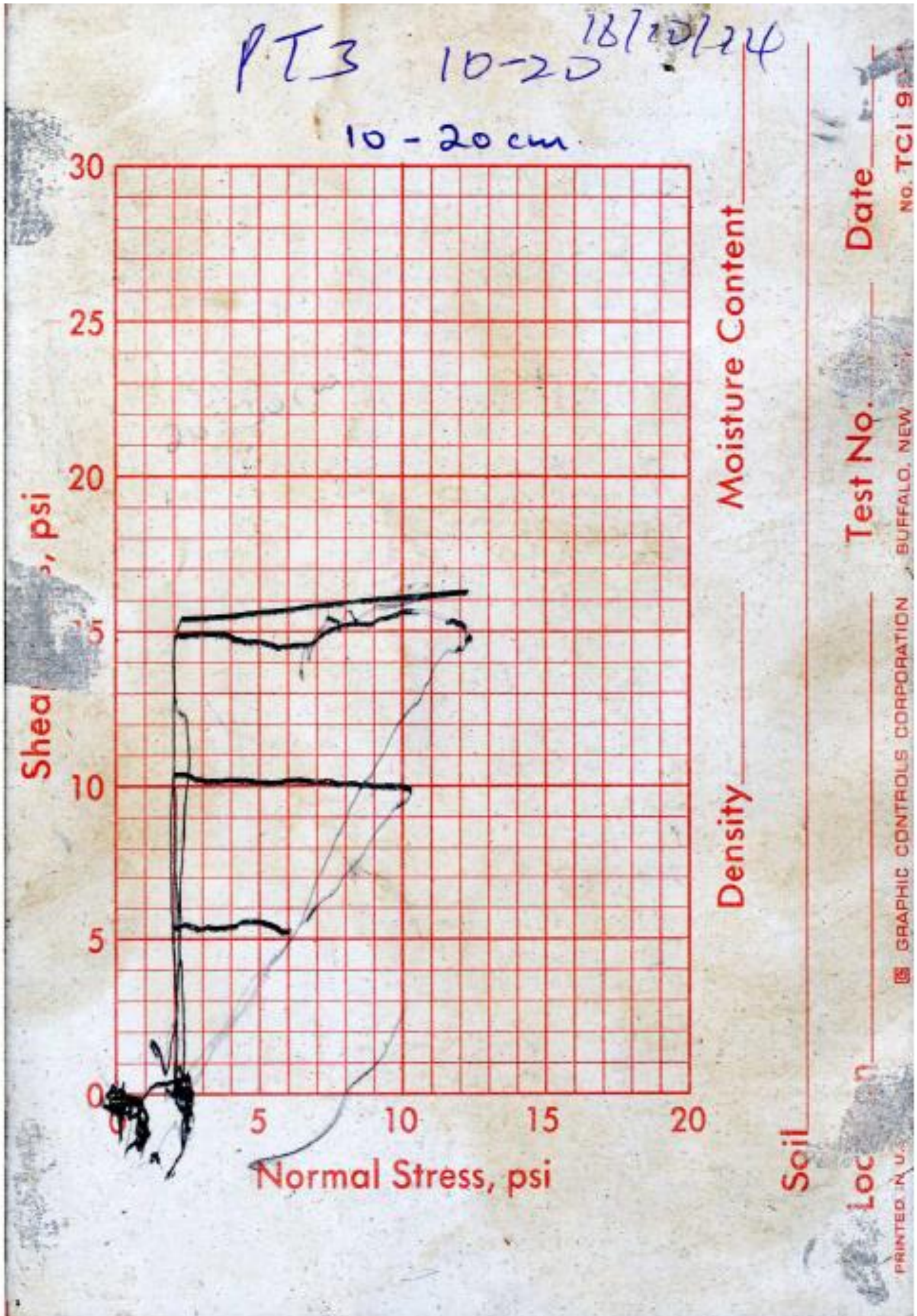
Zhang, C. B. Chen, L. H. Liu, Y. P. Ji, X. D. and Liu, X. P. (2010). Triaxial compression test of soil-root composites to evaluate influence of roots on soil shear strength. *Ecological Engineering*, *36*(1), 19–26.

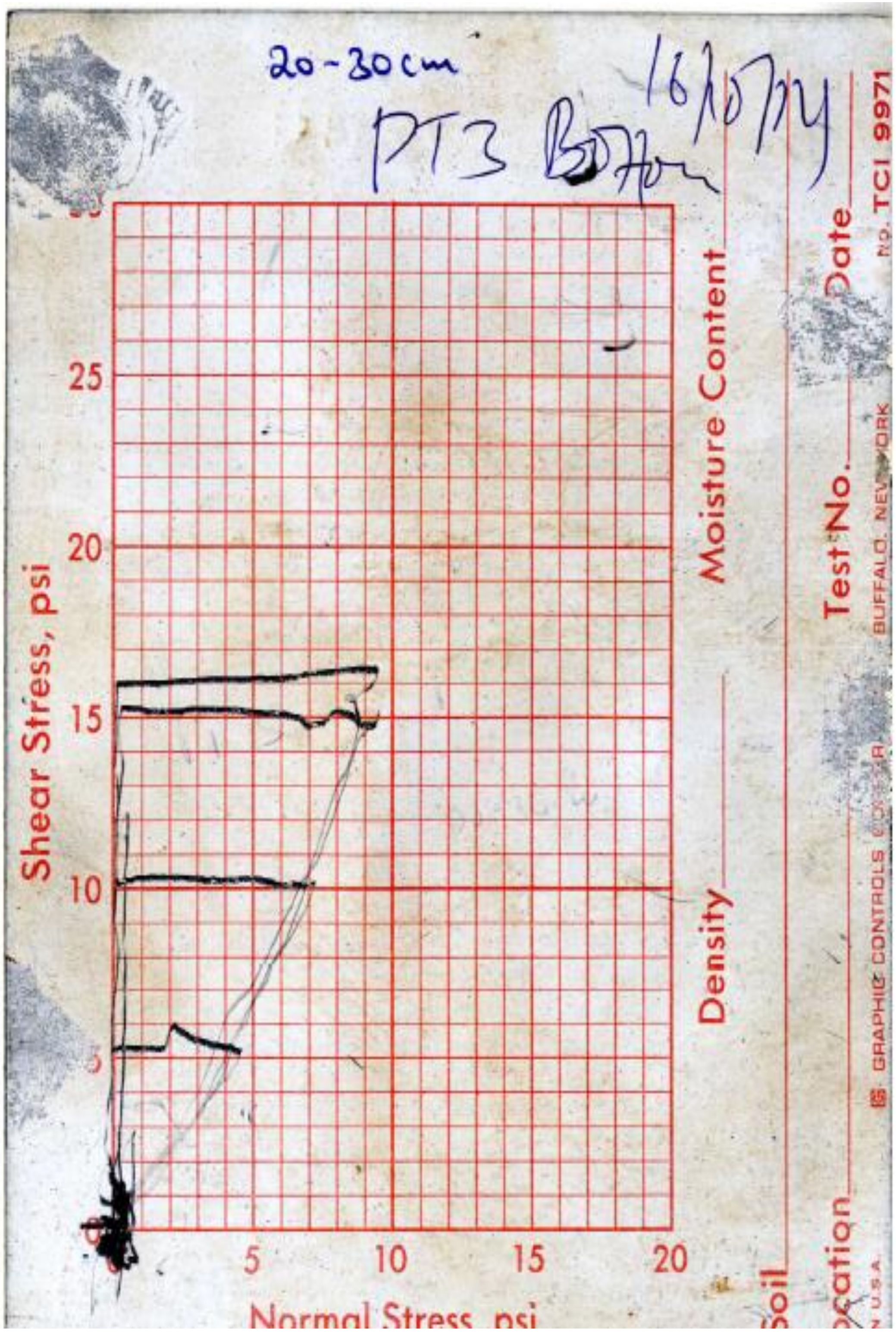
8. APPENDICES

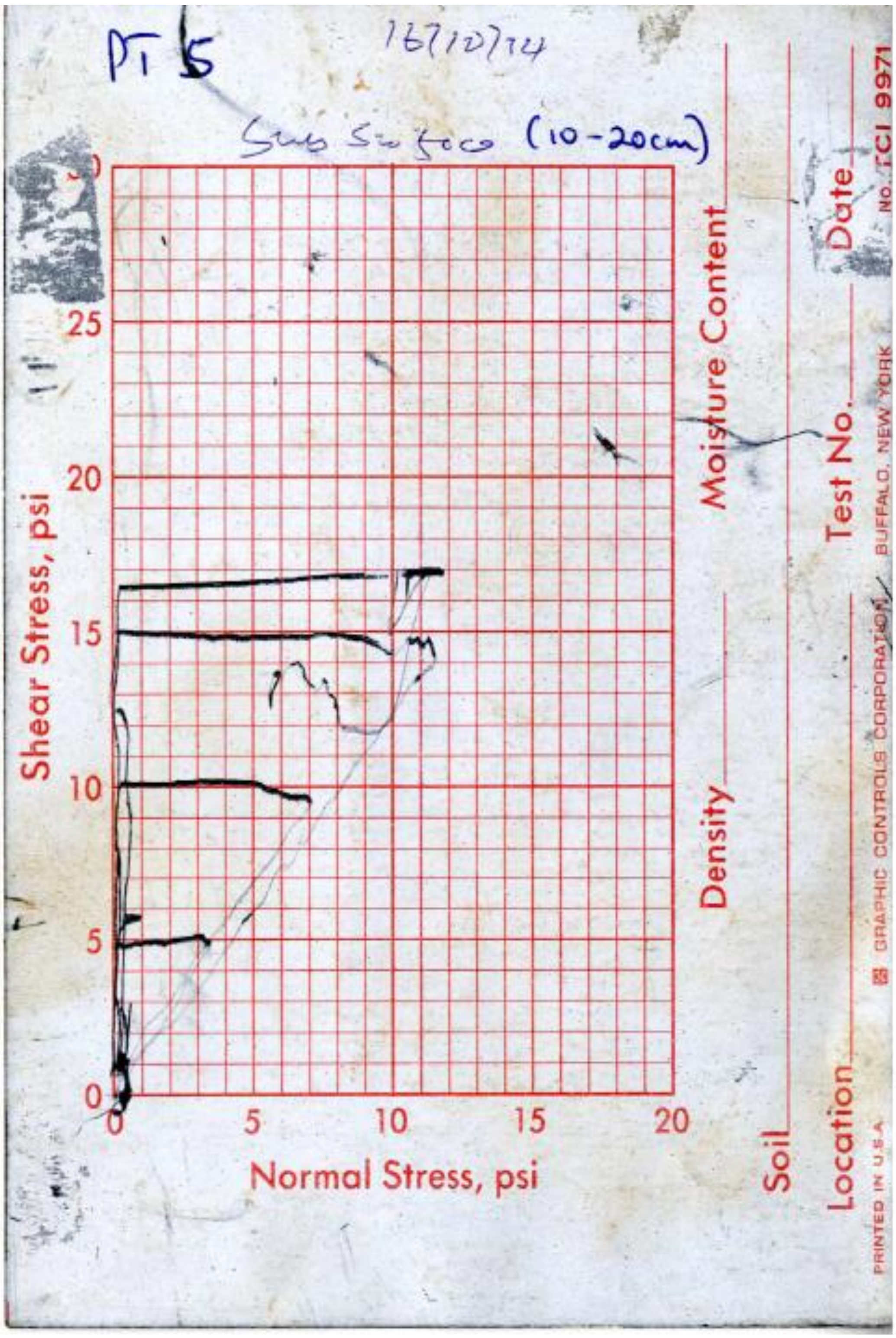
Appendix 1: Shear stress verses normal stress graphs for various holes

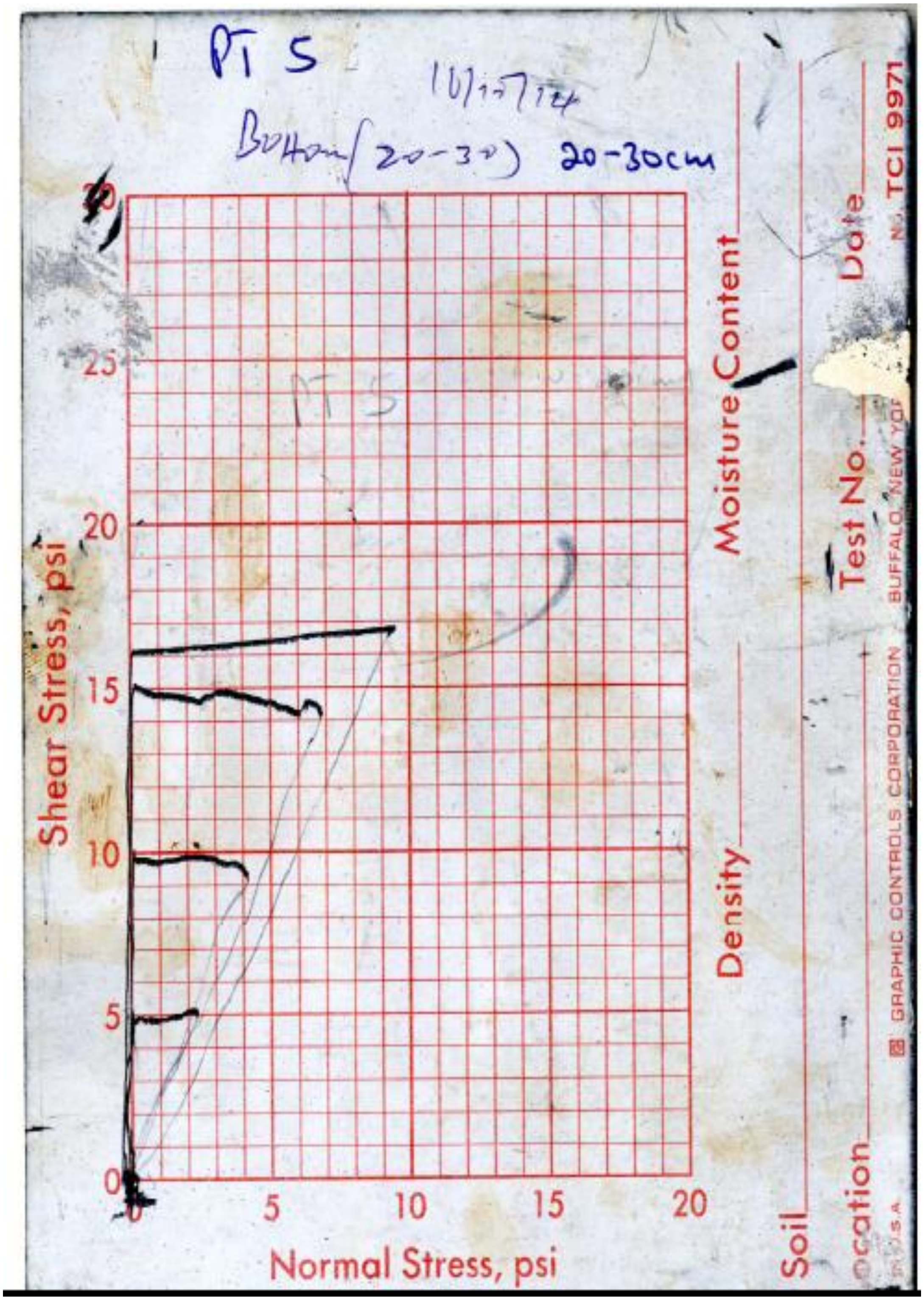



P1 10-20cm.
Shear Stress, psi
30
25
20
15
10
5
0
0
5
10
15
20
Normal Stress, psi
Moisture Content
Density
Soil
Date
Test No.
Location
No. TCI 9971
BUFFALO, NEW YORK
GRAPHIC CONTROLS CORPORATION
IN U.S.A.


PT3 10-20 18/10/24
10 - 20 cm
30
25
20
15
10
5
0
Shear Stress, psi
5
10
15
20
Normal Stress, psi
Moisture Content
Density
Date
Test No.
Soil
Location
GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK
PRINTED IN U.S.A.


20-30cm
PT3 Bottom
16/10/14
Shear Stress, psi
Normal Stress, psi
Moisture Content
Density
Test No.
Date
Soil
Location
NO. TCI 9971
GRAPHIC CONTROLS CORP. BUFFALO, NEW YORK


PT 5
16/10/14
(10-20cm)
Shear Stress, psi
0
5
10
15
20
25
Normal Stress, psi
0
5
10
15
20
Moisture Content
Density
Soil
Date
Test No.
Location
NO. TCI 9971
GRAPHIC CONTROLS CORPORATION, BUFFALO, NEW YORK
PRINTED IN U.S.A.


PT 5
10/17/14
Bottom (20-30) 20-30cm
Shear Stress, psi
0
5
10
15
20
25
0
5
10
15
20
Normal Stress, psi
Moisture Content
Density
Soil
Location
Date
Test No.
No. TCI 9971
GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK

Appendix II: List of Definitions

AIDS: Acquired Immuno Deficiency Syndrome

Analysis of Variance (ANOVA): Is a statistical method used to test differences between two or more means.

Concretions: Soil-structural units which are irreversibly cemented together.

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.

Conventional tillage: Tillage operations traditionally performed in preparing a seedbed for a given crop and grown in a given geographical area.

Covering depth: The thickness of soil with which materials are covered by an implement.

Draft: The force to propel an implement in the direction of travel

Edge-clearance angle: The effective angle which is included between the line of travel and a line drawn through the back or non-soil working surface of the tool at its immediate edge.

Effective operating width: Operating width minus overlap.

Ground clearance: Minimum vertical distance between the soil surface and a potentially obstructing machine element.

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

HIV: Human Immunodeficiency Virus

Implement width: The horizontal distance perpendicular to the direction of travel between the outermost edges of the implement.

Internal Friction angle (φ): Is the measure of the shear strength of soils due to friction.

Lift (rake) angle: The angle, in a vertical plane parallel to the direction of travel, between a tool axis and the soil surface.

Line of travel: The line and direction along which the tillage implement travels

Mechanical impedance: The resistance to the movement of plant parts or tillage tools through soil that is caused by the mechanical strength of the soil.

Mechanical stability (strength): The degree of resistance of soil to deformation.

Minimum tillage: The least soil manipulation necessary for crop production or for meeting tillage requirements under existing soil conditions.

Moisture content of soil: Is the ratio of the mass of water in a sample to the mass of solids in the sample, expressed as a percentage.

Moldboard plowing: Primary tillage which is performed through mouldboard plow to shatter soil with partial or complete soil inversion

No-till: A system where crops are grown in narrow slots or tilled strips in previously undisturbed soil. Soil disturbance is typically limited to that required for placement of fertilizer and/or seed, for clearing residue from the seed row and to no more than one third of row width. Plant residue is maintained on the soil surface year-round.

of soil immediately below tillage depth created by mechanical pressure and/or soil-shearing forces.

Operating overlap: The distance perpendicular to the direction of travel that an implement reworks soil previously tilled.

Operating width: The horizontal distance perpendicular to the direction of travel within which an implement performs its intended function.

Orientation, tool: The position of the tool in a framework of cartesian coordinates which is usually oriented with the soil surface and the direction of travel. Orientation is specified in side, tilt, and lift angles as a minimum.

Primary shear surfaces: The initial and distinct surfaces appearing during failure which are caused mainly by shear.

Rake Angle: Forward angle between the face of the tool and horizontal soil surface

Reduced tillage: Any tillage or seeding system that maintains 15–30% residue cover on the soil surface after during the critical erosion period -or is a system which consists of fewer or less energy intensive operations compared to conventional tillage.

Scouring (shedding): A soil-tool reaction in which soil slides over the surface of the tillage tool without significant adhesion.

Secondary shear surface: Shear surfaces which result from the twisting, pushing, or tumbling of the soil after or during the initial displacement. Secondary shear surfaces are often perpendicular to the primary shear surfaces.

SED: Standard Error of Difference

Shank: A structural member primarily used for attaching a tillage tool to a beam or a standard.

Shear blocks (or clods): The blocks of soil which are sheared loose from the main soil mass by tillage tool action.

Shear Strength: Is a measure of the soil resistance to deformation by continuous displacement of its individual soil particles.

Shear surfaces: Failure surfaces occurring where the soil has sheared.

Side angle: The angle, in the soil surface plane, between a tool axis and a line which is perpendicular to the direction of travel.

Side force (side draft): The horizontal component of pull perpendicular to the line of motion.

Soil compaction: The act of reducing the specific volume of soil.

Soil cutting: Separation of a soil mass by a slicing action.

Soil failure: The alteration or destruction of a soil-structural condition by mechanical forces such as in shearing, compression, or tearing.

Soil reaction: The soil response to the application of mechanical forces.

Soil shatter (pulverization): The general fragmentation of a soil mass resulting from the action of tillage forces.

Soil sliding: The sliding of soil across a surface.

Soil throw: The movement of soil in any direction as a result of kinetic energy imparted to the soil by the tillage tool.

Soil-tool geometry: The configuration of the soil-tool boundary. The overall shape is usually oriented with the direction of travel of the tool and the soil surface.

Soil-working surfaces: Portions of tillage tools which are designed to be in contact with soil.

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

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

Tillability: The degree of ease with which a soil may be manipulated for a specific purpose.

Tillage depth: Vertical distance from the initial soil surface to specified point of penetration of the tool.

Tillage, primary: That tillage which constitutes the initial major soil-working operation normally intended to reduce soil strength, cover plant materials, and rearrange aggregates.

Tillage, secondary: Any of a group of different tillage operations, following primary tillage, which are designed to create refined soil conditions before seeding to create specific soil surface configurations or to control weed growth.

Tillage: The mechanical manipulation of soil conditions for the enhancement of crop production.

Tool clearance: The minimum distance in a specified direction between a point on the tool and the nearest potentially obstructing implement element.

Tool overlap: The distance perpendicular to the direction of travel in which a tool-operating width coincides with the operating width of another tool.

Tool width: Maximum horizontal projection of a tool in the soil perpendicular to the line of motion.

Tool-operating width: The maximum horizontal distance perpendicular to the line of motion over which a tool performs its intended function.

Tool-skip area: The area of soil surface left undisturbed during passage of a tool.

Appendix III: Regression for the 100 mm depth

Regression statistics

Regression statistic	Statistic value
Multiple R	0.503948
R Square	0.253963
Adjusted R Square	0.005284
Standard Error	0.616454
Observations	5

Analysis of variance

Source	df	SS	MSS	F_{ratio}	P-value
Regression	1	0.38809	0.38809	1.021249	0.386655
Residual	3	1.140045	0.380015		
Total	4	1.528135			

Regression coefficients

Coefficient	Coefficient value	Standard Error	t-Statistic	P-value
Intercept	4.4548	1.012936	4.397907	0.021791
X Variable 1	-0.0197	0.019494	-1.01057	0.386655

Appendix IV: Regression for the 200 mm depth

Regression statistics	
Regression statistic	**Statistic value**
Multiple R	0.765342
R Square	0.585748
Adjusted R Square	0.005284
Standard Error	0.305848
Observations	5

Analysis of variance

Source	**df**	**SS**	**MSS**	**F_{ratio}**	**P-value**
Regression	1	0.396806	0.396806	4.241977	0.131546
Residual	3	0.280628	0.093543		
Total	4	0.677435			

Regression coefficients

Coefficient	**Coefficient value**	**Standard Error**	**t-Statistic**	**P-value**
Intercept	5.4838	0.502559	10.91175	0.001647
X Variable 1	-0.01992	0.009672	-2.05961	0.131546

Appendix V: Regression for the 300 mm depth

Regression statistics	
Regression statistic	**Statistic value**
Multiple R	0.999924
R Square	0.956478
Adjusted R Square	0.005284
Standard Error	0.020971
Observations	5

Analysis of variance

Source	**df**	**SS**	**MSS**	**F_{ratio}**	**P-value**
Regression	1	2.882717	0.960906	2185.016	0.015725
Residual	3	0.00044	0.00044		
Total	4	2.883157			

Regression coefficients

Coefficient	**Coefficient value**	**Standard Error**	**t-Statistic**	**P-value**
Intercept	83.053	0.195842	22.50806	0.028265
X Variable 1	1.1764	0.008908	8.085175	0.078341
X Variable 2	0.0082	8.74E-05	-14.0218	0.045326

Appendix VI: Sub-soiler Design