Tillage Effects on the Aggregate-Associated Organic Carbon and Bulk Density in Some South African Soils with Different Texture

By

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DECLARATION

I, **Sarah Kangai Njeru,** declare that the thesis hereby submitted for the degree of Master of Science in Agriculture (Soil Science) at the University of Fort Hare is my work and has not been previously submitted to another University.

Signature ....

Date ....13th February, 2016..........

Place: University of Fort Hare, Alice

PREFACE

Soils are the heart of terrestrial ecosystems. For the soils to fully function, it is necessary to keep them in good health. Nevertheless, the physical part of the soil is fast deteriorating. This study was carried out to contribute to the efforts of mitigating soil degradation. The study focussed on the soils of semi-arid region in South Africa.

This thesis consists of six chapters, which mainly focus on soil organic carbon, texture, mineralogy, compaction and their interactions under tillage. Chapter one gives the background information, problem statement, justification for conducting the study, and objectives. Chapter two reviews the literature relevant to the study. Chapter three gives the materials and the methods used in the experiments. Chapter four contains findings of the study. Chapter five discusses the findings from the experiments presented in chapter four in details. The sixth chapter contains the conclusions and recommendations drawn from the findings. References cited in the study are listed after chapter six. Appendices containing outputs of statistical of data presented in this study appear at the end of the document.

Writing of this thesis was possible through the help of my supervisor professor IIC Wakindiki for his expert input. Special thanks to friends, my family and colleagues for the moral and professional inputs. Lastly, I acknowledge the funding from the Govern Mbeki Research and Development Centre through the Research Niche Area for Sustainable Agriculture.

DEDICATION

Thesis dedicated to my loving family.

ABSTRACT

Tillage operations disrupt the soil structure resulting in aggregates of various sizes and altered bulk density. Moreover, tillage influences soil carbon pools and many other soil physical properties. The objectives of this study were to determine, in various South African soils under different tillage systems, the following. (1) Amount of aggregate-associated soil organic carbon (SOC), (2) soil compressibility, and (3) relationship between compressibility, texture and the aggregate-associated SOC. The soil samples used in this study were collected from six different sites in Eastern Cape Province, South Africa. Soil samples were taken from conventional tillage (CT) and no-till (NT) land. To keep the soil aggregates intact sampling was done using a spade and carefully carried to the laboratory in rigid containers. For SOC determination, treatments were the two tillage systems, CT and NT, and four aggregate sizes. The experimental design was completely randomized design with a factorial layout and was replicated three times. Aggregate-associated SOC was determined using Walkley-Black method. Proctor compaction test was used determine the dry bulk density with varying moisture content and consequently the maximum bulk density (MBD) and critical water content (CWC). The aggregate-associated SOC content differed with tillage system and was significant higher ($p < 0.05$) in CT than NT. The amount of aggregate-associated SOC was 1.67 times higher in CT than NT plots. The MBD ranged between 1.77 g/cm^3 and 10.27 g/cm^3 and the CWC ranged from 9.1% to 10.3%. The higher amounts of SOC in CT were attributed to the annual crop residue returns while the lower amounts of SOC in the NT fields were due to grazing. Therefore, tillage influenced the amount of aggregate-associated organic carbon irrespective of the resulting size of the aggregate. The positive relationship between tillage and aggregate-associated SOC challenges the conversion of land to v no-till for carbon sequestration. The overall gradient for correlation between the MBD and CWC was negative with $r^2 = 0.23$ and a p value of 0.0076. The compressibility curves indicated higher values under CT if the texture class was silt clay.

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LIST OF ABBREVIATIONS AND ACRONYMS

SOC	Soil organic carbon
SOM	Soil organic matter
TOC	Total organic carbon
CCs	Cover crops
SIC	Soil inorganic carbon
NT	No-till
T	Tilled
CT	Conventional tillage
DF	Degrees of freedom
DBD	Dry bulk density
MBD	Maximum bulk density
CWC	Critical water content
AGS	Aggregate size

CHAPTER ONE

1.0 INTRODUCTION

Land degradation is a top challenge limiting soil productivity in South Africa partly because of declining soil physical condition (Bennie and Hensley 2004, van Rensburg 2010). Some of the obvious consequences of declining soil physical condition include loss of fertile top soil and contamination of surface water bodies by runoff (Bennie and Hensley 2004, van Rensburg 2010). Consequently, over the years there has been a surge in research aimed that alleviating land degradation and improving soil productivity. In this regard, many researchers such as Murungu et al. (2011), Gichangi and Mnkeni (2010), Thulasizwe and Simeon (2013) and Kamota et al. (2013) have focused on soil fertility improvement for plant nutrition. The few reports that are available on the soil physical aspects mostly deal with the effects of tillage systems on soil organic matter (SOM) content (Blanco-Canqui and Lal 2007; Du Preez et al. 2011). Land use affects the quality of soils; with soil physical properties more affected compared to chemical properties (Getachew et al. 2012). Due to susceptibility of physical quality, there is need for land management systems that focus more on soil structure preservation. Such physical properties include water infiltration, bulk density and soil moisture content.

Soil structure condition is related to the SOC present in a soil. However, a major scientific gap exists because there is not enough information that relates SOC dynamics to mechanical properties of individual macro- and micro aggregates under different land use systems. However, it is generally known that there is a fundamental linkage between aggregate size and the overall soil structural stability. Soil aggregation influences soil behaviour such as erodibility, organic matter protection, fertility and productivity (Bronick and Lal 2005). Increase in proportion of macro-aggregates and reduction in micro-aggregates improves the structural integrity of soils (Blanco-Canqui et al. 2011).

Soils that have high proportion of macro-aggregates possess a larger pore space, higher infiltration rate and improved aeration (Nimmo 2004, Six et al. 2000). Macro-aggregates have high affinity for SOC (Blanco-Canqui and Lal 2007). Likewise, macro-aggregates are associated with improved density and compressibility; an important soil physical properties influencing soil productivity.

1.1 Problem Statement

Many South African soils are degraded and have poor physical properties (Bennie and Hensley 2004) and low SOC. The degradation is mostly on the physical aspect of the soil unit. Efforts to address soil degradation through environmental friendly soil management practices has not entirely succeeded probably because there is little understanding of the role of SOC and physical properties at soil aggregate level in South African soils.

1.2 Justification

Understanding the interaction between SOC and the soil physical properties will help in optimising soil management systems for enhanced productivity. Soil physical property qualities depend on the characteristics of the individual aggregates and hence soil structure. Individual aggregate properties such as stability, strength and size determine the susceptibility of the bulk soil to degradation and the structural integrity. Soil bulk density, moisture and compressibility are also key properties especially under large scale farming where there is use of machinery for farm operations.

1.3 Objectives

The aim of the current study was to establish if the size of individual aggregates had any influence on associated SOC and some other mechanical soil properties in various South African soils under different tillage systems. The following were the specific objectives.

(1) To determine the amount of aggregate-associated SOC in various South African soils under conventional and no-till systems.

(2) To determine the compressibility of various South African soils under conventional and no-till systems.

(3) To determine the relationship between compressibility, texture and the aggregate-associated SOC of various South African soils under conventional and no-till systems.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Soils have optimum production potential when they possess certain quality properties. Good quality soils are characterised by good aeration, proper infiltration rate, appropriate bulk density, tolerable strength and good aggregation (Nimmo 2004). However, this is not always the case because many soils get degraded, due to factors such as erosion, continued mono-cropping, intensive tillage and nutrient harvesting. Erosion alone can cause soil loss of up 50 t/ha annually (Paterson et al. 2013). Consequently, sustainable soil management projects are being done to reduce the rate of soil degradation. Such soil management projects include promotion of the soil structure integrity through approaches such as minimum tillage and enhancing SOC sequestration by incorporating SOM (Le Bissonnais and Arrouays 1997, Bossuyt et al. 2002, Wick et al. 2009). Management-induced changes in SOC are the main determinants of soil aggregate characteristics such as stability size and strength. Soil aggregation is important a number of applications. Aggregate stability and size distribution may be used to predict various agricultural techniques such as tillage, organic matter additions and erosion by wind and water (Nimmo and Perkins 2002).

2.2 Tillage influence on soil organic carbon and aggregate characteristics

Soil carbon is present in soils in both organic and inorganic forms such as lime or carbonates especially in drier areas. The carbonates modify the aggregation especially in macro-aggregates. In presence of inorganic carbon, stability of macro-aggregates may be enhanced because the carbonates decelerate decomposition of organic matter, which holds particles together (Fernández-Ugalde et al. 2013). The soil inorganic carbon (SIC) is found on varying amount depending on the region, with the desert biome containing the largest amounts (Rasmussen 2006). The top 0 to 20 cm soil contain about 0.38 % SIC depending on the prevailing soil forming processes (Shi et al. 2012). Soils rich in carbonates have more massive aggregates and have less porous structure than the decarbonated soils. In the soil environment SOC is reputed to play a greater role compared to SIC. Chenu et al. (2000), Wakindiki and Yegon (2011) found that SOC improved aggregation, combating the excessive force of raindrops and detachability of soil particles thereby reducing soil loss during surface flow. The SOC decreases the wettability of aggregates thereby increasing their cohesion through the cementing of mineral particles via organic polymers. Fuentes et al. (2009) found that SOC influenced the relative amount of macro and micro aggregates in the soil

Tillage affects the soil structure and consequently the productivity (Flanzluebbers and Stuedman 2010). Minimum structural disturbance, when performing field operations, preserves soil structure integrity. The quality of a soil can be indicated by the amounts of SOC present. The SOC differs according to the land use and is different when land is cultivated or uncultivated.

Cultivated soils contain less amounts of SOC compared to soils, which are intact (Zhang et al. 2005). A study done by Zhang et al. (2005) showed that amounts of SOC in wetland was 78.2 g/kg, upland forest was 33.3 g/kg, abandoned cultivated land 30.2 g/kg and in cultivated land it was 21.4 g/kg. In some instances cover crops (CCs) are used to improve SOC through leaf fall (Abdollahi and Munkholm 2014).

Soil disturbance through tillage affects the soil characteristics especially near the soil surface (Flanzluebbers and Stuedman 2010). Their study on Hiwassee series fine loamy, siliceous, thermic, Rhodic Kanhapludult (sandy clay loam) showed that SOC varied with depth and was highest at upper layers and decreased down the profile. Many researchers, for example, Bennie and Hensley (2004), Van Rensburg (2010), Mandiringana et al. 2010, Nciizah and Wakindiki (2012), have reported low SOC in soils in Eastern Cape Province. Nevertheless, tillage practices that contribute to degradation of SOM are common. In general, the top soil in most of the South African soils is the most affected (Mills and Fey 2004). If soils are tilled without regard, the amount of carbon stocks can rapidly decrease within a short time. For instance, Lobe et al. (2001) found out that soil carbon stocks reduced by 50 % within a period of 3.5 years of conventional tillage. Mikha et al. (2013) compared conventional and no-till systems effects on carbon stocks on silt loam soils in a semi-arid area of Akron, United States of America and noted changes within seven years. In the no-till plots soil SOC increased by 3.2 Mg/ha but in tilled land SOC decreased by 0.5 Mg/ha. Therefore, it was concluded that SOC changes with time depending on tillage system.

Organic matter from the leaves and other organic residue acts as a cementing agent for soil aggregates hence improving soil structure. Rapture energy of soil aggregates is higher when there is crop cover (Blanco-Canqui and Lal 2008). In an experiment, Blanco-Canqui et al. (2007) found that the energy required for macro-aggregate to disintegrate was 10.11 µJ in forest, 4.09 µJ in pasture and 0.91 µJ in mould board ploughed land. Tillage makes aggregates unstable and readily dispersed when there is raindrop impact due to this low rapture energy. Tillage breaks the soil aggregates exposing them to increased degradation of aggregate-associated SOM (Li et al. 2007; Schjønning et al. 2002). Zero tillage preserves the soil structure but intensive tillage systems cause soil disturbance leading to a decline in SOC and aggregate stability within a short time. During tillage the fungal hyphae that bind the soil particles are cut causing the soil aggregates to disintegrate, whereas no-till encourages soil aggregation. In addition, farming methods and soil disturbance activities that prevents accumulation of organic matter lead to poor aggregates formation and break up of already existing aggregates (Elmholt et al. 2008).

The SOC that contributes in binding the soil particles together is usually protected in the individual aggregates (Blanco-Canqui and Lal 2007). Aggregate stability serves as the main indicators of the soil quality status (Six et al. 1998). The larger the proportions of stable macro-aggregates, the more stable the soil structure. The SOC may be protected against microbial attack when adsorbed in clay minerals (Six et al. 2000). However, tillage breaks the aggregates disrupting them leading to increased aggregate turnover, hence more SOM decomposition (Six et al. 1998). Aggregate size influences the SOC turnover. Dameni et al. (2010) found that aggregate size was inversely proportional to the amount of SOC. However, in some instances there was no significant relationship between the various aggregate sizes and associated SOC (Bossuyt et al. 2002). Soil carbon is found in larger amounts in conventional tillage than no-till under a short term but under a long term carbon is more stable under no-till (Blanco-Canqui et al. 2007). Nevertheless, the amount of carbon differs with the aggregate size. There is more carbon protection at micro-aggregate level than at the macro-aggregate level (Bossuyt et al. 2002). Tillage does not directly influence macro-aggregate content in the soil but organic biomass, which in turn, affects the macro-aggregates. Silt content is negatively related to macro-aggregate content in the soil (Andruschkewitch et al. 2013).

2.3 Soil organic carbon and aggregate formation under no-till

Soil organic carbon can be responsible for up to 48% aggregate characteristics (Blanco-Canqui et al. 2007). Carbon sequestration is improved when more SOC is retained in the soils (Kong et al. 2005). Maintaining the soil intact ensures that SOC is not released in the atmosphere and the carbon is also not exposed to microbial attack (Bossuyt et al. 2005). A study done by Li et al. (2007) showed that aggregate stability differed with tillage system. The mean weight diameter was 0.97 mm in CT, 1.03 mm in no-till and 2.32 mm in no-till with mulch. It was concluded that uncultivated fields had greater aggregate stability reducing their susceptibly to agents of degradation (Li et al. 2007), which helped the soil to remain productive giving optimum yields.

2.4 Soil organic carbon, bulk density and critical water content

Soil organic carbon is found imbedded within individual aggregates. Therefore, breakdown of aggregates leads to release of SOC. Conversely, less soil aggregate disturbance maintains SOC (Wiesmeier et al. 2012). Changes in SOC concentration due to tillage can have significant effect on bulk density and critical water content (CWC) (Blanco-Canqui et al. 2010). Trials conducted over a period of 12 years showed that total SOC was 47.0 Mt/ha in no-till, 43.7 Mt/ ha in chisel plough and 37.7 Mt/ha in mould board plough (Olson et al. 2005). Organic matter is effective in alleviating disruptive forces that would otherwise cause loss in soil productivity. A study by Blanco-Canqui et al. (2011) showed that crop cover reduced near surface bulk density by 4% and increased wet aggregate stability 2 times and SOC concentration 1.3 times compared to areas without ground covers. Soil management practices have great effect on bulk density (Blanco-Canqui et al. 2005). Soils with potentially better structural quality but associated with low bulk density are more susceptible to degradation (Zhang et al. 2001). Soil bulk density influences factors such as root emergence and other soil physical properties such as compressibility (Ruehlmann and Martin 2009). Mechanical properties of soils differ with the size of the aggregate. For instance a study done by Blanco-Canqui and Lal (2008) showed that the tensile strength of aggregate size of 4.75-8 mm was higher than that of 3.3-4.75 mm.

2.5 Contribution of individual aggregate characteristics to the overall soil structure functioning

Stability refers to the ability of soil aggregate to resist rapture when subjected to external forces such as tillage, and erosion agents. Aggregates are the main indicators of soil status as shown by the number of stable aggregates (Six et al. 2000). Stable aggregates indicate a stable soil structure. Large pores spaces associated with stable macro-aggregates serves as points of aeration and water movements in soils (Nimmo 2004). Root penetration and growth is also favoured by the presence of macro-pores, which contributes to better agronomic production. Aggregate structure influences soil surface hydrology including runoff, infiltration and redistribution (Nimmo 2004). Unstable aggregates disintegrate easily and are more prone to agents of erosion. When the macro-aggregates disintegrate into micro-aggregates and particles, they block the soil pores. Loose soils encourage formation of seal after a rainstorm and crusts when the soil dries up (Nciizah and Wakindiki 2015).

2.6 Relationships between bulk density, texture and organic carbon under different tillage systems

Prevailing land degradation and consequent loss of productivity has been attributed to the continuous soil disturbance through tillage practices in many parts of Africa (Fowler and Rockstrom 2001). Particularly, frequent tillage operations on farms have been said to result in compaction leading to deterioration of the soil physical component. Soil compaction, especially from heavy traffic, occurs as a result of pressure being exerted on soil aggregates leading to a decline in the amount of macro-pores (>30 μm), poor drainage and reduced aeration. Compaction causes harmful effects to the soil such as reduced infiltration, poor aeration, increased surface runoff and poor root penetration (Ishaq et al. 2001). However, compaction does not always have adverse effects. Sometimes it has beneficial aspects such as increasing the contact area between the roots and soil particles for increased efficiency in water and nutrients uptake (Lepiec et al. 2003).

Compaction is influenced by both internal and external factors acting on the soil. Some of the internal factors include mineralogy, texture, organic carbon and water content. Soil texture, especially clay content influences the proctor density (Nhantumbo and Cambule 2006. Some of the external factors affecting compaction are the energy applied, soil mass and the soil management practices such as cover cropping. For instance, a study by Blanco-Canqui et al. (2010) on gearly silt loam soils showed that cover crops are able to alleviate near surface increase in bulk density, which would have otherwise lead to soil compaction. Similarly Smith et al. (1997) studied the compressibility of a loamy sand soil and clay soil. The range from initial to maximum bulk density (MBD) was 0.1Mg/cm^3 in loamy sand soil and the range in clay soil 0.6 Mg/cm^3/ 0.5. The energy as an external factor can be as a result of raindrops, cattle trampling, animal/human, harvesters and tractor movement during various farm operations (Milne and Haynes 2004). Additionally, compatibility varies with water content resulting to varying bulk density. The MBD and CWC show the maximum level of compaction in a soil.

The Proctor test provides the compactibility of disturbed soils over a range of water content. Compaction test with proctor test apparatus gives dry bulk density, which varies with water content in soil. The graph of dry bulk density against water content yields a compressibility curve. The highest point of the compressibility curve yields MBD and corresponding water content known as CWC due to its adverse effect (Etana et al. 1997). The CWC is the water content that results in the greatest density for a specified compactive effort. Compacting soils, at moisture content higher than CWC, results in soils that have unstable dispersing structure. The compacted soils at moisture content beyond CWC are also more susceptible to swelling and less susceptible to shrinking hence easily displaced (Labelle and Jaeger 2011) with the MBD being the reference point. Soils compacted less than MBD result in flocculated soil structure. The MBD is used to determine the relative bulk density which is the absolute value between MBD and non-compacted bulk density. Relative bulk density is important in assessing the effect of bulk density because soil properties such as texture will cause soils to differ in bulk density even when subjected to similar management practices (Smith et al. 1997).

To maintain good soil health it is of importance to know when the soils are at risk of compaction and how various operations such as tillage are likely to affect soil. However, information on soil compaction is inconsistent where compaction seem to be a course of land degradation and an effect of land degradation as well. Poor soil physical quality due to compaction will result to reduced soil production potential and further increase in production costs. Friable soils enable proper root growth especially in crops such as carrots where the roots are used as storage organs.

Compaction may last in soils for many years (Etana et al. 2013) Knowledge of dry bulk density and CWC is important in timing of field operations in order to avoid compaction. Field operations such as tractor harvesting should be done under favourable conditions that are under low moisture content. This moisture content varies from one soil type to another. Additionally, under wet soil conditions the soils have low mechanical resistance and are at a higher risk of compaction.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Sampling sites

The study was conducted at the university of Fort Hare laboratories. Soil sampling was done in selected sites in Eastern Cape Province, South Africa. The sampling sites were either under conventional tillage or no-till. The soil samples were collected from a semi-arid environment.The sampling sites include Mbems koedlosvei both fallow and tilled, Alice jozini, Pandulwazi jozini Ngwenya Swartland and Mamatha. The geographical location of the sampling sites is as shown in the Figure 1.

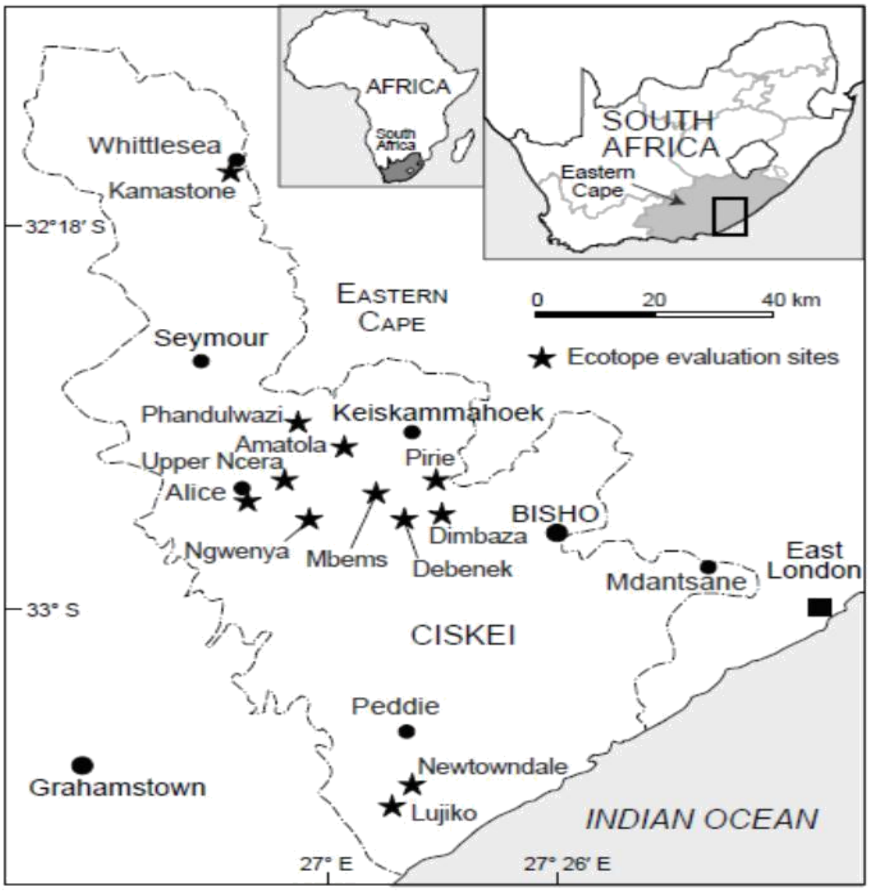

Figure 1. A map of soil sampling site (Nciizah and Wakindiki 2012).

3.2 Sampling procedure

The soil samples were taken from the upper 20 cm using a spade. The sampling depth of 20 cm was chosen because most SOC is found in the topmost soil layer (Flanzluebbers and Stuedman 2010). Sampling entailed taking random 20 spots per site and then mixing them to get a composite sample. The samples were carefully labeled and carried to the lab in rigid containers to avoid breaking of the aggregates. Air-drying was done by spreading the soil on the benches in the laboratory. Large soil clods were cautiously fragmented with the hands to get smaller aggregates. After air drying the soil, samples were put in bags labeled and stored until when needed.

3.3 Experiment 1. Tillage effects on aggregate-associated soil organic carbon in some South African soils

The objective of this experiment was to determine the amount of aggregate-associated organic carbon in various aggregate sizes in soils with different texture and mineralogy under conventional and no-till systems.

3.3.1 Soil organic carbon

The SOC was determined using Walkley-Black method as described by Rowell and Coetzee (2003). The bulk soil was sieved to get four aggregate classes for each of the area sampled. Obvious rocks, roots and plant materials were removed to increase data accuracy. The soil samples of various aggregate sizes; 2 to 3 mm, 3 to 4 mm, 4 to 5 mm and >5 mm were ground with a mortar and pestle separately then made to pass through a 0.35 mm sieve. One gram of the sieved soil sample was wet oxidized using potassium dichromate. Titration was then done using ferrous ammonium sulphate. The amount of aggregate-associated SOC was calculated using equation 1.

$$Organic\ C\,\% = \frac{[cm^3\ of\ Fe(NH_4)_3(SO_4)_2\ blank - cm^3\ of\ Fe(NH_4)_3(SO_4)_2\ sample] \times M \times}{0.3 \times f\ Soil\ mass\ (g)}$$

Equation 1

Where,

M is the concentration of Fe $(NH_4)_3(SO_4)_2$ in mol dm^{-3}

f is recovery factor = 1.3

3.3.2 Experimental design and statistical analysis

The experimental setup was a completely randomized design with factorial treatment arrangement. One factor was aggregate size, which was tested at four levels and the second factor was tillage system at two levels. Each treatment combination was replicated to minimize the experimental error. Analysis of variance for a completely randomized design with a factor arrangement was done using JMP® version 11.1 (SAS 2012). Means separation were done using Fischer's protected least significant differences at $P < 0.05$.

3.4 Experiment 2. Compressibility of some South African soils under conventional and no-till systems

The objective of this experiment was to determine the CWC and MBD of various soils under conventional and no-till systems. The study hypothesised that soil disturbance through tillage, texture differences and soil organic carbon has effect on MBD and CWC. Soil MBD and CWC were tested at different tillage systems, soil texture and mineralogy. The tillage systems were conventional tillage and no-till. The textural classes were sandy loam, silt loam and silt clay loam. Experiments were done to determine the compressibility, soil organic carbon and their relationship with texture and tillage system used.

3.4.1 Proctor compaction test

The samples were collected from six sites. The sampling sites were either under tillage (conventional tillage) or no-till. Replicas of six different water contents were prepared for each soil sample and the stored over night to equilibrate. The moisture content varied from dry to near saturation for each soil sample. The samples were then compacted using a proctor apparatus (American Society for Testing and Materials, 2007). Proctor test allows determination of MBD and CWC. Proctor compaction test was done by 25 blows is three layers falling at a height of 30cm. The blows mimic the trampling and passage of tractors during the farm operations. The volume of proctor mould was 944.68 cm^3. The compacted sample within mould was weighed and then three sub-samples were collected top, bottom and the middle of proctor mould. The sub-samples were immediately weighed and then oven dried for 48 hours at 05 then eighed again for moisture content determination. Gravimetric water content of the subsample was extrapolated to that of the compacted soil and proctor dry bulk density (g/cm^3) was computed by dividing oven dry weight of the compacted soil by the volume of the proctor mould. Dry bulk densities were plotted against the levels of water content to obtain the proctor compaction curve.

3.4.2 Soil organic carbon

The SOC was determined using Walkley-Black method as described by Rowell and Coetzee (2003). Obvious rocks, roots and plant materials were removed to increase data accuracy. The soil samples ground with a mortar and pestle separately then made to pass through a 0.35mm sieve. One gram of the sieved soil sample was wet oxidized using potassium dichromate. Titration was then done using ferrous ammonium sulphate. The amount of aggregate-associated SOC was calculated using equation 2.

$$Organic\ C\% = \frac{[cm^3\ of\ Fe(NH_4)_3(SO_4)_2\ blank - cm^3\ of\ Fe(NH_4)_3(SO_4)_2\ sample] \times}{M \times 0.3 \times f\ Soil\ mass\ (g)}$$

(Equation 2

Where,

M is the concentration of $Fe(NH_4)_3(SO_4)_2$ in mol m^{-3}

f is recovery factor = 1.3

3.4.3 Experimental design and statistical analysis

The experimental setup was a completely randomised design. Each treatment combination was replicated three times to minimise the experimental error. Analysis of variance for a completely randomised design with a factor arrangement was done using JMP® version 11.1 (SAS 20 2). Means separation ere done using Fischer's protected least significant differences at $P < 0.05$.

CHAPTER FOUR

4.0 RESULTS

4.1 Some properties of studied soils

There were three sites under conventional tillage and 3 under no-till system. The texture analysis showed three textural classes which included silt clay in Mamatha, silt loam in Alice jozini and all the other sites had silt clay loam texture. The electrical conductivity ranged between 34.50 and 80.97µSm^{-1} with Mamatha and Mbems koedosvelei highest with both under CT. The pH was slightly acidic with low of 5.50 and high of 5.78. In mineralogy quartz was the dominating mineral ranging between 68.11 and 86.85. There were other minerals present and are shown in table 1. However, kaolinite and smectite were noticeably absent (Table 1).

Table 1. Soil initial characteristics. (adapted from Nciizah and Wakindiki 2012)

Site	Tillage	Textural Class	EC (μSm^{-1})	Climate	pH	Soil mineralogy (%)						
						H	K	Mi	Mu	P	Q	S
Alice jozini	CT	SL	47.9	SA	5.78	0.29	-	4.40	6.10	12.2	77.01	-
Phandulwazi Jozini	NT	SCL	37.80	SA	5.49	0.58	-	0.98	3.98	7.64	86.85	-
Mbems Koedosvelei	NT	SCL	55.17	SA	5.65	0.43	-	5.52	6.46	12.2	75.32	-
Mbems Koedosvelei	CT	SCL	80.97	SA	5.76	0.65	-	4.69	7.76	10.5	76.37	-
Ngwenya Swartland	NT	SCL	53.57	SA	5.53	0.66	-	7.50	6.51	17.2	68.11	-
Mamatha	CT	SC	34.50	SA	5.50	0.43	-	5.52	6.46	12.2	75.32	-

CT = Conventional tillage, NT = No-till, SL= Silt loam, SCL= Silt clay loam, SC=Silt clay, EC= Electrical conductivity, SA = Semi-arid, H = Hematite, K = Kaolinite, Mi = Microline, Mu = Muscovite, P = Plagioclase, Q = Quartz, S = Smectite

4.2 Experiment 1. Tillage effects on aggregate-associated soil organic carbon in some South African soils

The experiment was carried out to test if tillage and aggregate size had any effect on the aggregate-associated SOC. The amount of aggregate-associated SOC was 1.67 times higher in tilled than no-till plots which were 1.70 and 1.02 respectively.

Table 2: Tillage effects on aggregate-associated Soil Organic Carbon (SOC)

Land use	**Mean aggregate-associated SOC**
Conventional tillage	1.70^{a}
No-till	1.02^{b}

The different superscript letters indicate means were significantly different.

The aggregate-associated SOC was highest in aggregate size of 4-5 mm at 1.41% and lowest in 3-4 mm aggregate size at 1.28%. There was no particular order of amounts of SOC in the aggregate size > 5 had 1.35 and 2-3 mm had 1.38. There was no significance difference in amount of aggregate associated SOC across all aggregate sizes (Table 3)

Table 3 Aggregate size effects on aggregate-associated Soil Organic Carbon (SOC).

Aggregate size (mm)	Least square mean	Stardard Error	Aggregate-associate SOC
2-3	1.38	0.09	1.38a
3-4	1.28	0.09	1.28a
4-5	1.41	0.09	1.41a
>5	1.35	0.09	1.35a

SOC= Soil organic carbon, a= not significantly different

The amounts of aggregate-associated SOC were significantly different between the two tillage systems at $p < 0.001$. However, there was no significant difference between aggregate sizes p value 0.7975 and no interaction between the tillage system and aggregate size the p value was 0.6741 (Table 4). Therefore, tillage influenced overall aggregate associated SOC content regardless of the aggregate size.

Table 4: Tillage and aggregate size effects on aggregate-associated Soil organic carbon

Source of variation	Nparm	DF	Sum of Squares	F Ratio	Prob > F
AGS	3	3	0.0819138	0.3386	0.7975
Tillage	1	1	8.7427005	108.4034	<.0001**
Replicates	8	8	1.1109613	1.7219	0.1134
Tillage*AGS	3	3	0.1244189	0.5142	0.6741

DF= Degrees of freedom, ** Significant effect at $p < 0.01$, AGS=Aggregate size

4.3 Experiment 2. Compressibility of some South African soil under conventional and no-till systems

4.3.1 Effect of tillage, texture and mineralogy on critical water content and bulk density

Mbems koedosvelei under conventional tillage with silt clay loam texture had the highest CWC at 10.27 % and lowest MBD at 1.772 g/cm^3. Mamatha a silt clay soil had the lowest CWC at 9.143% and highest SOC at 1.78. Mbems koedosvelei a silt clay loam soil under no-till had the highest MBD. The results obtained for all the sites are as shown in Table 5.

Table 5: Means for maximum bulk density critical water content and soil organic carbon

Site	Tillage system	Texture	Critical water content (%)	Maximum Bulk Density (g/cm^3)	Soil organic carbon
Alice Jozini	CT	SL	9.227	1.875	1.72
Phandulwazi Jozini	NT	SCL	9.3	1.907	1.12
Mbems Koedosvelei	CT	SCL	10.27	1.772	1.64
Mbems Koedosvelei	NT	SCL	9.343	1,969	1.04
Ngwenya Swartland	NT	SCL	9.29	1.932	0.97
Mamatha	CT	SC	9.143	1.955	1.78

CT= Conventional tillage, NT= No-till, SL=Silt loam, SCL= Silt clay loam, SC= Silt clay

4.3.2 Conventional tillage and no-till

Soils were compacted at a range of six different moisture contents. With each moisture contents a different dry bulk density was achieved. From a graph of dry bulk density against moisture content was plotted and the result showed that as the moisture content increased the bulk density increased. However, after MBD further increase in moisture content caused a decrease in dry bulk density. The results gave the bulk density at various moisture contents with the trendline being the compressibility curve. From Figure 2, in both tillage systems, bulk density increased as the water content increased up 9 % soil moisture content and then then assumed a negative gradient. The bulk density in conventional tillage was consistently higher than in no-till at all moisture contents. The CWC was achieved at 9.3 % in both tillage systems. Conventional tillage had a higher MBD at 1.94 g/cm^3 whilst that of no-till was 1.91 g/cm^3.

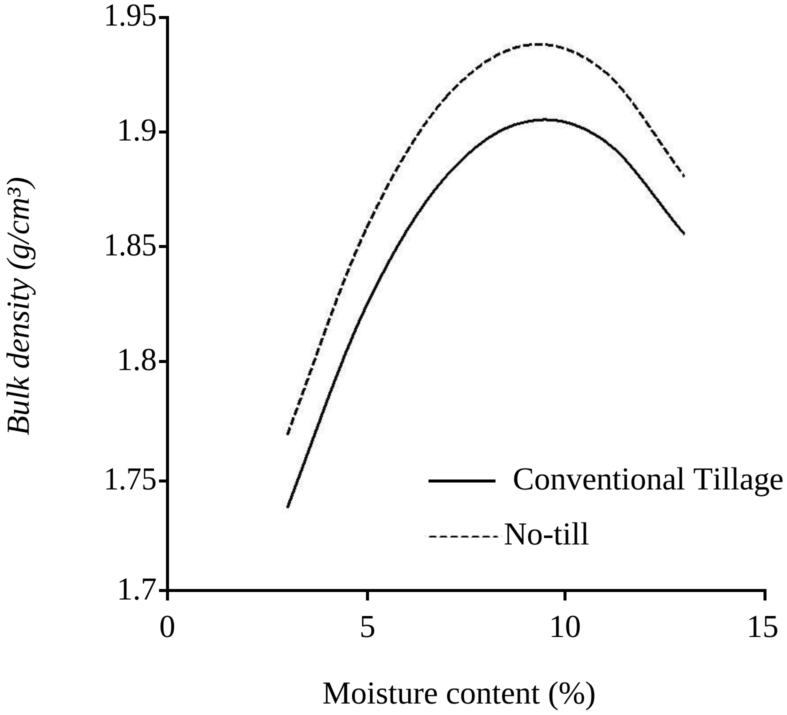

Figure 2**:** Compressibility of the various soils under conventional and no-till systems

Although the compressiblity was higher for tilled land land than no-till, the statistical analysis indicated no significance differences between the two tillage systems. There was no significance difference in CWC in both tillage system as the $p > 0.1826$ (Table 6). There was also no significant difference in MBD in the tilled and no-till $p > 0.0612$ (Table 7)

Table 6: Effect test of tillage on critical water content

Source of variation	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replicates	2	2	0.00240833	0.0087	0.9277
Tillage	1	1	0.57640833	2.0857	0.1826

DF = Degrees of freedom

Table 7: Effect test of tillage on maximum dry bulk density

Source of variation	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replicates	2	2	0.00180075	0.5367	0.4825
Tillage	1	1	0.01533675	4.5706	0.0612

Compactibilty was also tested at various textural classes including silt clay loam, silt clay and silt loam.Compaction curve varied with the textural class with the silt loam producing the highest MBD and CWC. The soil bulk density ranged between 1.6 g/cm^3 and maximum was attained 1.7 g/cm^3 for silt loam soils and at 2.1 g/cm^3 for silt clay loam (Figure 3).

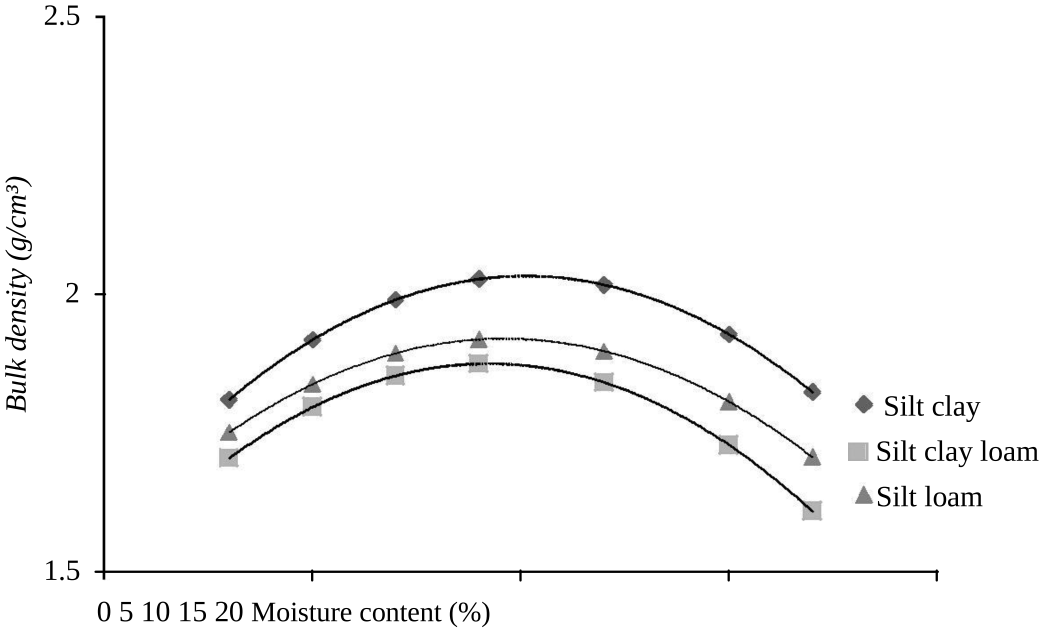

Figure 3: Compressibility of the various soils with different texture

Statistical analysis was run to determine the level of significance of the effect the texture on MBD and CWC. The result indicated no significant effect for all texture classes that is silt loam, silt clay loam and silt clay. The p value was 0.3202 (Table 8).

Table 8: Test effects on soil texture

Source of variation	DF	Sum of Squares	F Ratio	Prob > F
Texture	2	0.32100833	1.2140	0.3202
Replicate	3	0.75334583	1.8994	0.1659

DF= Degrees of freedom

4.3.3 Maximum bulk density and critical water content

Relationship was run for MBD and CWC. There was a negative correlation between water content and dry bulk density. This was done for combined means of all tillage systems and texture. The graph showed a negative correlation which at r^2 value of 0.53 The equation of the line was y = -0.09x + 2.8 (Figure 4)

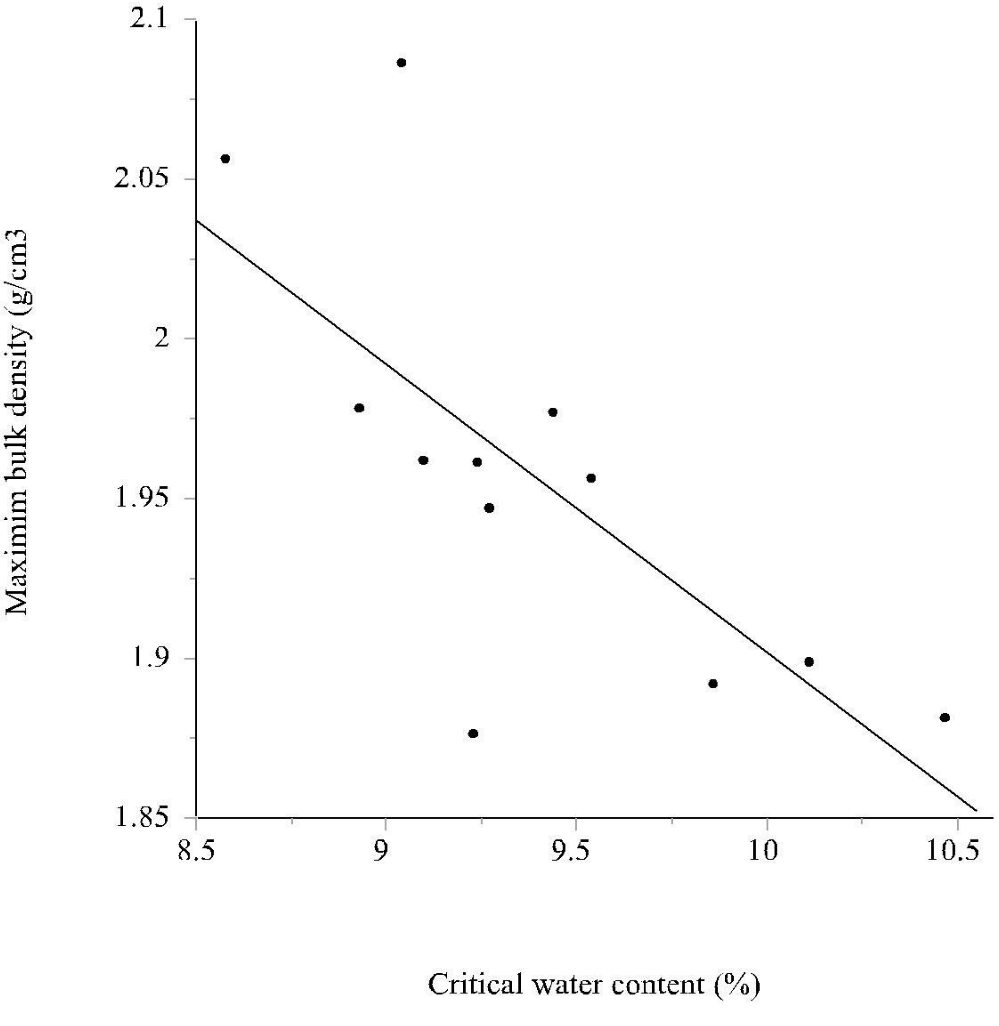

Figure 4: Maximum bulk density expressed as a function of critical water content

There was significant interaction between the MBD and CWC the intercept highly significant at $p < 0.0001$. The CWC had a significant effect on MBD which was significant at a p value of 0.0076 (Table 9).

Table 9: Relationship between maximum bulk density and critical water content

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.8030369	0.254691	11.01	<.0001**
CWC	-0.090111	0.027053	-3.33	0.0076*

** Significant effect at $p < 0.01$, * Significant effect at $p < 0.05$

4.3.4 Dry bulk density, moisture content and soil organic carbon

Analysis yielded positive relationship between CWC and SOC . The results obtained show low relationship between CWC and SOC at R^2 of 0.06 (figure 5). The level of interaction was also significant at a p value of < 0.0001. But the SOC did not have significant effect on CWC p was 0.0426 (Table 10).

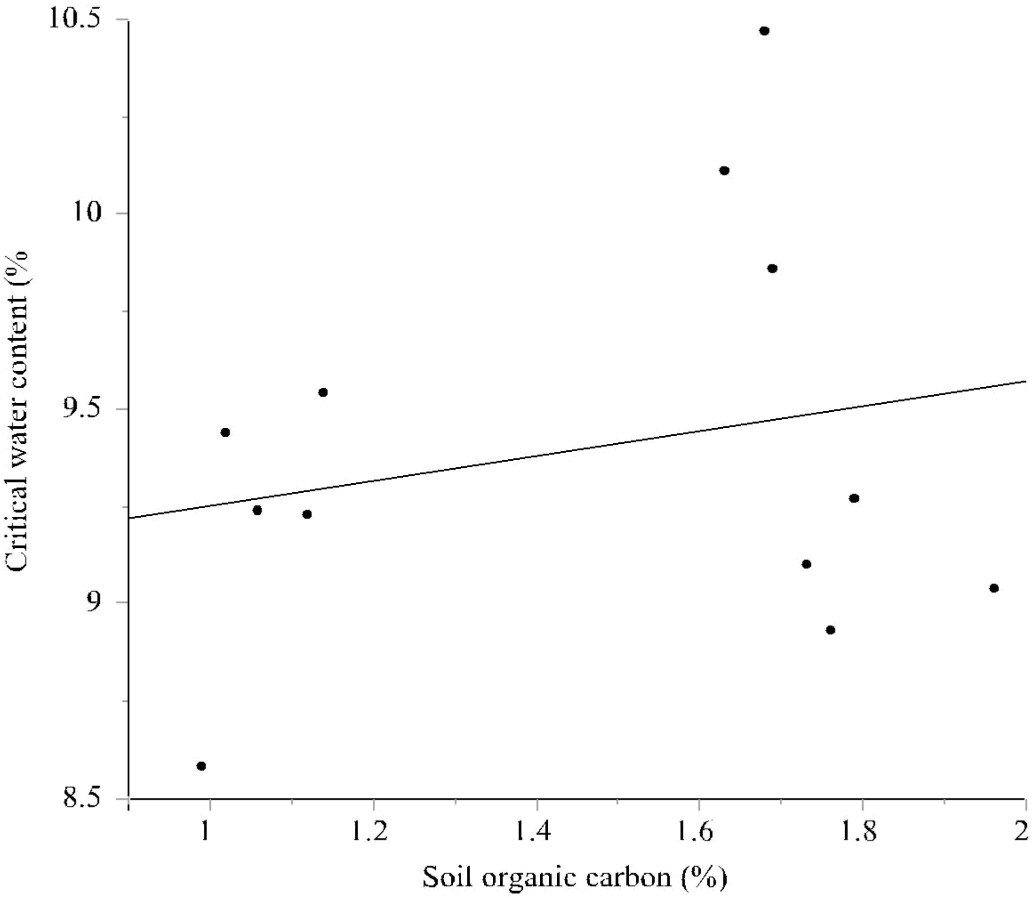

Figure 5: Relationship between soil organic carbon and critical water content

Table 10: Critical water content with respect to soil organic carbon content

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.2202316	0.027958	79.41	<.0001**
SOC	0.0545359	0.064871	0.84	0.4202

** Significant effect at $p < 0.01$

Relationship between the MBD and SOC was also tested. The graph obtained shows that there was low interaction at R^2 of 0.04 (Figure 6) which was highly significant at p ¸0.001. However, SOC had no significance significant effect as p value was 0.8431 (Table 11).

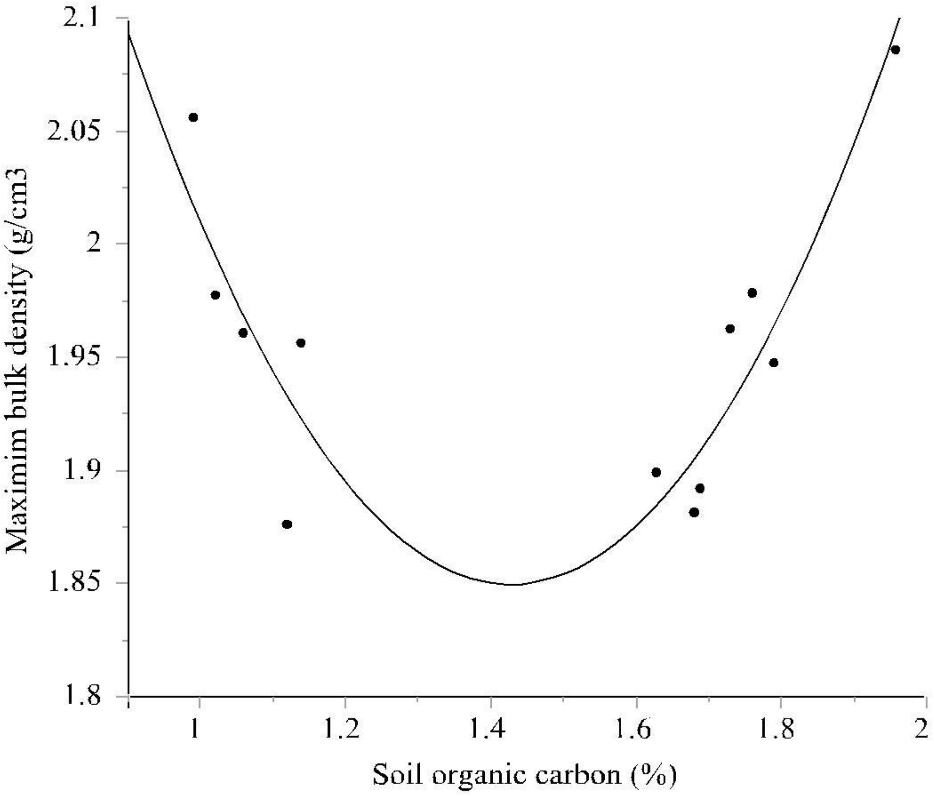

Figure 6: Soil organic carbon and maximum dry bulk density relationship

Table 11: Soil organic carbon and maximum bulk density statistical relationship

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	0.6732148	0.017316	38.88	<.0001*
Soil organic carbon	-0.008161	0.040178	-0.20	0.8431

CHAPTER FIVE

5.0 DISCUSSION

5.1 Experiment 1. Tillage effects on aggregate-associated soil organic carbon in some South African soils

Tillage resulted in higher mean aggregate-associated SOC than no-till (Table 2). Although some studies such as that reported by Lobe et al. (2001) indicate contrary results, others like Mikha et al. (2013) agree that tillage may increase aggregate-associated SOC in the short run because in the long term SOC is more stable under no-till (Blanco-Canqui et al. 2007). The higher amounts of aggregate associated SOC under conventional tillage could be due to the annual increment of organic residue. Agronomic practices such as planting cover crops, which was observed in most sampling sites, enhance SOC turnover in soils (Blanco-Canqui et al. 2011). Tillage is also known to incorporate organic matter (Blanco-Canqui et al. 2007), which would otherwise remain on the soil surface separated from soil particles. On other hand, no-tilled land was used for natural pasture, which was intensively grazed robbing the soil of the annual SOC turnover. Moreover, the sampling sites were in a semi-arid region (Table 1). Semi-arid areas have low vegetation cover, which could have aggravated the low contents of aggregate-associated SOC in the no till areas. The low aggregate associated SOC values could also be explained by the low correction factor that arises due to the method used. The correction factor usually gives lower SOC values under no-till compared to tilled land by 15 %.

Generally, the aggregate-associated SOC values were relatively low in both tilled and no-till land (Table 2). Clay content and type of a soil are known to affect aggregate associated SOC. The soil mineralogy in the study sites was mainly quartz (Table 1). Quartz rich soils are very efficient in SOC emission (Webb et al. 2013). Such emissions would reduce the amount of aggregate-associated SOC. On the other hand, kaolinites and smectite were noticeably absent in all the soil samples (Table 1). Clay minerals such as kaolinite and smectite are reputed to hold SOC intimately (Jindaluang et al. 2010). The absence of kaolinite and smectite could have been the reason for the low amounts of aggregate-associated SOC across all soils. The relationship between aggregate size and aggregate associated SOC is inconclusive. Whereas some researchers such as Dameni et al. (2010) reported an inverse relationship, in this study there was no significant effect of aggregate sizes on aggregate associated SOC. Likewise, Bossuyt et al. (2002) made similar observations.

5.2 Experiment 2. Compressibility of some South African soil under conventional and no-till systems

5.2.1 Tillage and compressibity

Although all the soils were subjected to the same treatment the response varied across the tillage used this shows tillage effects on soil. There was a higher MBD in the conventionally tilled land than in no-till. Similar results were observed by Lipiec and Hakansson (2000). The MBD increased as moisture content increased this region of positive linear relationship between the change in between dry bulk densities and moisture content is referred to as problematic region. The region is problematic because increase in water content results in critical increase in bulk density and adverse effect for plant growth (Labelle and Jaeger 2011). After CWC is point the soil no longer becomes compacted but the soil particles begin to disperse. The dispersed soil structure may be hazardous since it is prone to factors such as mass wasting. Plants may also be carried away during erosion. The MBD shows the highest dry bulk density that can achieved. At MBD aeration is poor, water infiltration is low and the soils are prone surface runoff and erosion. However, the tillage practices affect the point at which MBD is achieved. From Figure 2, conventionally tilled land had higher MBD than the no-till land indicating that under the same compression forces the conventionally tilled land becomes more compacted than no-tilled land. The higher compressibility of conventionally tilled land could be attributed to the organic matter and the pore sizes from ploughed land. Soils with high pore spaces have a high compressibility (Smith et al. 1997) and ploughing is linked with the increase of macro-pores in the soil hence the higher compressibility in tilled sites. Tillage incorporates the organic matter and increases the ratio of macro-pores in the soil therefore higher compressibility in conventional tillage. The higher compressibity in no-till land is an indication that no-till land has better mechanical resistance so under the same conditions of tractor wheel movement, animal trampling and human movement

However there were no significant differences between the two tillage systems in both MBD and CWC. This could be due to the management practices on the conventionally tilled land for example constant organic cover on the ground that made it similar to the no-till land. The close relationships could also have been due to the similar soil properties in both tillage systems. Figure 1 shows that the soils collected were under similar climatic conditions. The mineralogy was similar as it is clear that the dominating primary mineral was quartz while smectite and kaolinites were noticeably absent. This can be an implication that soils with soils with similar endogenic properties are likely to respond alike when subjected to compaction even though the land use is different.

5.2.2 Texture, maximum bulk density and critical water content

The compressibility, texture analysis show that the dry bulk density and the moisture contents were different depending on the particle sizes (Nhantumbo and Cambule 2007). The soils with silt clay combination had a higher MBD. From the literature, soils containing silt and clay proportions are most susceptible to compaction especially when wet and the SOC is also low (Smith et al. 1997). Soil compaction causes a dense soil with few large pores, poor drainage and reduced aeration, especially in wet soils with low organic matter content and high proportions of silt or clay. With compacted subsoil layers, roots will be concentrated more in the upper layers and thus explore a smaller soil volume. This will lead to reduced water and nutrient uptake, reduced yields

5.2.3 Critical water content, maximum bulk density and soil organic carbon

Soil organic carbon is closely associated with many soil physical characteristics. Aragon et al. (2000) found that organic carbon had a relationship with MBD and SOC. Though low there was a interaction between SOC, MBD and CWC indicating that SOC influences soil physical characteristics. However the results here showed no significant relationship between SOC with CWC as well as MBD. This indicated that the SOC did not have influence on both parameters. The organic carbon influence will vary with the region

(Aragon et al. 2000). This could be the reason why the soils in our study SOC had no significance on MBD and CWC.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Experiment 1. Tillage effects on aggregate-associated soil organic carbon in some South African soils

Tillage influenced the amounts of aggregate-associated SOC. There was 1.67 times higher amounts of aggregate-associated SOC in CT than in NT land. Aggregate size did not affect the amount of SOC. Higher amounts of aggregate-associated SOC were contained in the small size fraction. The positive relationship between tillage and aggregate-associated SOC challenges the conversion of land to no-till for carbon sequestration. It is desirable to put more land under tillage. Nonetheless, since only two tillage systems were compared in this study, there is need to investigate more tillage systems and their combinations. The study covered the soils dominated by quartz, so it would be worth knowing how other minerals such as kaolinite and smectite would respond to tillage.

6.2 Experiment 2. Compressibility of some South African soil under conventional and no-till systems

Proctor compaction test can be used in determining the density of disturbed soils at various moisture contents. A graph of dry bulk density against water content showed increase in dry bulk density with increase in water content to a certain level then it decreased with increasing water content. The maximum level shows that the soil is at maximum compaction where all the pore spaces are depleted, hydraulic conductivity is low and there is likelihood of anaerobic respiration due to poor aeration. The correlation between the MBD and CWC was a clear implication that compaction varied with the moisture contents. The compressibility was compared between two tillage systems, CT and NT. Conventional tillage had a higher compressibility than no-till. This indicates that tilled land had higher mechanical resistance to compaction while no-till is more susceptible. Soil compressibility was also influenced by the soil texture. Comparison on textural classes on silt clay loam, silt clay and silt loam showed highest compressibility in silt clay and silt loam had the lowest.

The findings of this study enlighten on the degree of compaction at various moisture content in SC, SCL and SL textural classes and in tilled and no-till land. The information is useful to farmers in timing of field operations and to the researchers on the expected soil behaviour under studied conditions. The study contained mixed particle sizes an experiment with a dominant particle size would be more informative. Compaction can occur in several ways, the study focused on the impact as a cause of compaction so a study can be done to determine compaction resulting from rotating objects like tractor wheels.

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APPENDICES

Appendix 1: Tillage and aggregate size test effects on soil organic carbon

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
AGS	3	3	0.0819138	0.3386	0.7975
Tillage	1	1	8.7427005	108.4034	<.0001*
Replicate	8	8	1.1109613	1.7219	0.1134
Tillage*AGS	3	3	0.1244189	0.5142	0.6741

Appendix 2: Mean soil organic carbon per aggregate size

Aggregate size (mm)	Least Sq Mean	Std Error	Mean
2-3	1.3837617	0.06693684	1.38376
3-4	1.4026829	0.06693684	1.40268
4-5	1.4460879	0.06693684	1.44609
>5	1.3530101	0.06693684	1.35301

Appendix 3: Mean Soil organic carbon in the tillage systems

Level	Least Square Mean	Std Error	Mean
CT	1.7448486	0.04733149	1.74485
NT	1.0479228	0.04733149	1.04792

Appendix 4: Test effects of Tillage on CWC

Source of variation	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replicates	2	2	0.00240833	0.0087	0.9277
Tillage	1	1	0.57640833	2.0857	0.1826

Appendix 5: Effects test of tillage on maximum bulk density

Source of variation	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replicate	1	2	0.00180075	0.5367	0.4825
Tillage	1	1	0.01533675	4.5706	0.0612

Appendix 6: Effect test of soil texture on maximum bulk density

Source of variation	DF	Sum of Squares	F Ratio	Prob > F
Texture	2	0.32100833	1.2140	0.3202
Replicate	3	0.75334583	1.8994	0.1659

Appendix 7: Relationship between maximum bulk density and critical water content

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.8030369	0.254691	11.01	<.0001*
CWC	-0.090111	0.027053	-3.33	0.0076*

Appendix 8: Soil organic carbon and critical water content relationship

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.2202316	0.027958	79.41	<.0001*
SOC	0.0545359	0.064871	0.84	0.4202

Appendix 9: Relationship between soil organic carbon and maximum bulk density

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.6732148	0.017316	38.88	<.0001*
SOC	-0.008161	0.040178	-0.20	0.8431