RESILIENCE TO CRUSTING OF SOILS UNDER CONVENTIONAL TILLAGE AND CONSERVATION AGRICULTURE

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DECLARATION

I, Tshigoli Vhonani Lucadia, student No:11630455, hereby declare that this research dissertation for Master of Science (MSc.) in Agriculture (Soil Science) submitted to the Department of Soil Science, School of Agriculture, University of Venda has not been submitted previously for any degree at this or any other University. It is original in design and execution, and all references have been duly acknowledged.

Signed tshigodivl Date 04/ 09/2020

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ABSTRACT

Soil resilience is the ability of a soil to recover its function or capacity after applied stress such as crusting. Some soils have high potential for recovery while others have poor resilience. Soils with poor resilience are much more vulnerable to degradation. Many soils in South Africa are susceptible to crust formation, which affects many soil surface properties and processes and hence productivity. The objectives of this study were to demonstrate how soil resilience to crust formation is affected by conventional tillage and conservation agriculture in selected soils in South Africa. Soil samples were collected from four different soils (Hutton, Shortland, Glenrosa and Dundee) using PVC pipes with the length of 20 cm and diameter of 5cm and scanned using micro xray computed tomography for total pores. Total porosity from Luvisols, Ferrosols, Leptsols and Fluvisols under both conventional tillage and conservation agriculture was used to find soil resilience index. Soil crusting was influenced by both soil texture and clay mineralogy. The dominance of kaolinitic mineral caused the soil to be more stable as compared to soil dominated by quartz. Luvisols, Ferrosols and Leptsols were more stable and had aggregate stability of 57%, 69,5% and 32,7%, respectively. On the other hand, Fluvisols had poor aggregate stability with the value of 14,2%. Total porosity was in the order of 34,3%>32,2%>23,5%>16,3% for Ferrosols, Luvisols, Leptsols and Fluvisols, respectively. Soil crusting influenced the total porosity. Tillage practices had influence on soil crust formation hence, total porosity of the soils. Total porosity was higher under conservation agriculture as compare to conventional tillage. Resilience total porosity was in the order of 37,5> 23,9> 4,1> -30,1 on Luvisols, Ferrosols, Leptsols and Fluvisols, respectively. Soil resilience to crust formation was influenced by tillage practices. Soil resilience of Luvisols, Ferrosols and Leptsols can be achieved through conservation agriculture however, soil resilience of Fluvisols can be achieved through conventional tillage.

Keywords: Soil resilience, soil crusting, soil structure, aggregate stability, tillage practices, conservation agriculture.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Most of the soils in South Africa are susceptible to degradation arising from crust formation (Laker 2004), especially under conditions of low organic matter (Mills and Fey 2004b; Materechera *et al*. 2007). Materechera *et al*. (2007) found crusting on red sandy soil of Luvisols in parts of North West province. In addition, Mills and Fey (2004b) observed soil crusting in Limpopo, Mpumalanga, KwaZulu-Natal and Eastern Cape provinces. About 60% of soils in South Africa have ≤ 0.5% soil organic matter (Swanepoel *et al*. 2017). Soil organic matter increases cohesion between mineral particles leading to improved soil structure (Laghour *et al*. 2016). Conversely, low soil organic matter promotes poor soil structure prone to crusting and other forms of degradation.

Soil structure degradation limits soil productivity and because of its significance in agriculture, it has been studied for a long time and at various scales. Soil crusting is one aspect of soil structure degradation (Assouline 2004; Singer and Shainberg 2004). A soil crust is a thin dense layer formed at the soil surface. Soil crust is characterized by higher bulk density and lower porosity than the under layer (Hu et al. 2012). For example, Miriti *et al*. (2013) conducted a study on sandy loam soils. In this study these authors found that on soil with soil crust strength of 0,15 MPa the bulk density was 1,40 Mg m^{-3} lower than on soil with soil crust strength of 0,47MPa with 1,51 Mg m^{-3} higher in bulk density. These authors further observed that porosity was 47,04% on non-crusted soil and 43,14% on crusted soils.

Soil crust is formed when soil aggregates breakdown, fill the large pores and consolidate at the soil surface (Wakindiki and Ben-Hur 2002). Crust formation affects many soil surface properties and process such as infiltration, runoff, and erosion (Belnap. 2001; Li *et al*. 2005). For example, Lado and Ben-Hur (2004) found that Kaolinitic and illitic soils which do not contain smectite are stable and have final infliltration rate >8.0 mm h^{-1}. Kaolinitic and illitic soils that contain some smectite and smectitic soils are unstable with final infiltration rate < 4.5 mm h^{-1} (Lado and Ben-Hur 2004). Lado and Ben-Hur (2004) also found that runoff to be 40, 2 mm -51,8 mm in unstable soil (montmorillonitic soils) and 15,8 mm lower runoff in kaolinitic soil. Lado and Ben-Hur (2004) found soil loss to be 0,33 kg m^{-2} higher in kaolinitic soils and 1,141,24 kg m^{-2} in unstable soils. The presence of crust also imposes a mechanical resistance to seedling emergence (Fox *et al*. 2004; Materechera *et al*. 2007). Materechera *et al*. (2007) reported that seedling emergence of Bambara groundnut in crusting sandy soils in North West Province was 68% lower compared with 87.9% in non-crusted soil. Crust formation can be managed by practices such as tillage. For example, conventional tillage breaks down soil aggregates (Six *et al*. 2000; Sainju *et al*. 2009). Six *et al*. (2000) found that macroaggregates between (250-2000 µm) in conventional tillage had 0,48g aggregate g^{-1} dry soil lower compare to 0,6g aggregate g^{-1} dry soil in conservation agriculture. Conventional tillage also promotes decomposition of organic matter (Six *et al*. 2000; Sainju *et al*. 2009). For example, Six *et al*. (2000) reported 26,34g C kg^{-1} under no till compare to 14,56g C kg^{-1} under conventional tillage. Organic carbon is a major soil particle binding agent (Al-Kaisi and Yin 2005).

Conversely, conservation agriculture has been promoted in recent decades (Nciizah and Wakindiki 2015) to boost soil resilience. Conservation agriculture refers to a practice in which soil cover is maintained through surface retention of crop residues under no till/zero tillage (Bhan and Behara 2014). Aggregate breakdown proceeds differently in different soils (Nciizah and Wakindiki 2014). For instance, in a study conducted by Wakindiki and Ben-Hur (2002), they observed variation in aggregate breakdown by slaking through fast wetting. The authors found that kaolinitic soils had 2,80 mm higher mean weight diameter compare to montmorillonitic which had 0,250,31 mm mean weight diameter, while soils dominated by quartz and feldspar had mean weight diameter of 0,84-0,87 mm. Gicheru et al. (2004) found that soil with aggregate stability of 32%-37% were most stable and less susceptible to crust formation compare to soil with aggregate stability <7%. Clay mineralogy is a main factor that determines aggregate stability. Lado and Ben-Hur (2004) reported that soils dominated by kaolinitic mineral are more stable. The presence of smectite is considered to make soil unstable. However, Lado and Ben-Hur (2004) reported that soil which contain smectite (>5%) most likely to be unstable and more susceptible to form crusts Nonetheless, soil resilience to structural degradation due to tillage or conservation agriculture is largely unknown in South Africa.

1.2 Problem statement

Cultivated soils are prone to crust formation. Moreover, they are often subjected to different intensities of tillage ranging from conventional tillage to zero tillage as in conservation agriculture. These operations may cause different degrees of soil structure degradation because different soils differ in their resilience. Resilience of soils under different soil use and management is not well studied and understood.

1.3 Justification

The demand for increased food production has traditionally been achieved through expanding area under cultivation. Nevertheless, productive agricultural soils in South Africa have reached a limit. Productive soils are becoming marginal mainly due to inappropriate use and management. Therefore, it is imperative to improve our knowledge on how different soils respond to different intensities of tillage because most soils in South Africa are susceptible to crust formation.

1.4 Aim and objectives

1.4.1 Aim

Demonstrate soil resilience to crust formation under conventional tillage and conservation agriculture in selected soils.

1.4.2 Objectives

(1) To determine soil resilience to crust formation under conventional tillage in selected soils in South Africa.

(2) To determine soil resilience to crust formation under conservation agriculture in selected soils in South Africa.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil structure degradation and crust formation

Soil structure influences the functioning of soils and the ability of soil to support plant and animal life (FAO 2003a; Dexter. 2002; Six *et al*. 2004). Many soil/ crops management practices are linked with the decline in soil structure which leads to soil degradation. One of the major forms of soil degradation is soil crusting (Auzet *et al*. 2004; Blanco-Canqui and Lal 2010).

Soil crusting is a process that occurs as a result of the breakdown of aggregates and dispersion of clay when the soil is exposed to rainfall (Bu *et al*. 2013). Soil crust is a thin dense layer formed on the soil surface with a higher bulk density and lower porosity than the under layer (Hu *et al*. 2012; Wu *et al*. 2014). For example, Miriti *et al*. (2013) conducted a study on sandy loam soils. In this study, the authors found that on soil with soil crust strength of 0,15 MPa, the bulk density was 1,40 Mg m^{-3} while on soil with soil crust strength of 0,47MPa the bulk density was 1,51 Mg m^{-3}. The authors further observed that porosity was 47,04% on non-crusted soil and 43,14% on crusted soils. Soil surface crust is one of the most significant features for soil degradation because it decreases infiltration, increases runoff, influences erosion (Gicheru *et al*. 2004; Li *et al*. 2005).

For example, higher runoff rate of 26.2 mm h^{-1} was observed on crusted soil compared to 20.5 mm h^{-1} on soil with no crust in a semi-arid region in Limpopo Province (Mzezewa and van Rensburg, 2011). Crust also imposes a mechanical resistance to seedling emergence (Fox *et al*. 2004). For example, Materechera *et al*. (2007) reported that in North West Province on sandy soil, soil crusting hindered seedling emergence of Bambara groundnut. Seedling emergence on crusting soils was 68% while under non-crusted soil was 87.9%. In addition, Fox *et al*. (2004) reported that crusting inhibited emergence of *Chloris guyana* grass over a four-week period with the value of ±70% emergence on crusted soil and ±90% emergence on non-crusting soil.

In a study conducted by Manyevere *et al*. (2015), the author found poor seedling emergence of cotton due to soil crusting.

The stability of the soil aggregates against disruptive forces is of more importance in the prevention of soil degradation through processes of soil crusting (Nciizah and Wakindiki 2015). Soils which are highly aggregated have high tendency to resist aggregate breakdown and are less likely to form crusts (Levy and Mamedov. 2002; Algayer *et al*. 2014). According to Manyevere *et al*. (2016) soils with high clay content contain sesquioxides which help to promote aggregate stability, hence, reduce crust formation. In addition, Belnap. (2001) found that soils that are susceptible to crusting have poor aggregate stability. Moreover, aggregate stability promotes soil ability to withstand physical forces associated with raindrop impact or rapid entry of water into the soil which influences breakdown of soil aggregate, soil dispersion and consequently soil erosion (Kuykendall 2008). Any process or factor that enhances soil aggregation decreases soil crusting.

One of the factors that influences soil aggregation is organic matter content. For example, Zaher *et al*. (2005) found that organic matter can reduce slaking by modifying aggregate stability. In addition, (Chenu *et al*. 2000; Blanco-Canqui and Lal 2004) found that soil organic matter acts as a binding agent between soil particles and a waterabsorbing agent, thereby reducing clay wetting. This reduction in clay wettability reduces rapid water intake from 1-32 seconds and the subsequent pressure within entrapped air pockets, which reduces by 97% subsequent aggregate breakdown through slaking (Chenu *et al*. 2000). The cohesive forces holding the particles together determine the extent to which the aggregate can be detached (Wuddivira *et al*. 2009). High organic matter >2,0% (Chenu *et al*. 2000) leads to formation of macroaggregates which are resistant to slaking (Shirani *et al.* 2002; Pagliai *et al*. 2004; Materechera 2009).

2.2 Crust formation in different soils

There are no conclusive results on the influence of soil particle distribution on soil crusting (Nciizah and Wakindiki 2015). For example, Mamedov (2006) reported that an increase in clay content reduces crust formation because clay particles bind aggregates together contributing to cohesive strength of the aggregates. Fox *et al*. (2004) reported that soils with high silt and or fine sand contents are most likely to form crust due to their low aggregate stability. Similarly, Gicheru *et al*. (2004) found that crust was formed in soils with high fine sand and silt as they are less stable. Furthermore, Valentin (2005) observed that in sandy soils, crusts form where silt+ clay content exceeds 5% and most severe crusting observed for silt+ clay of 10%. However, Mills and Fey (2004b) observed that clay content plays only a minor role in crust formation in South African soils.

Clay mineralogy is a main factor that determines aggregate stability and consequently surface sealing, runoff and soil loss (Lado and Ben-Hur 2004). Clay dispersibility capacity is an important characteristic which determines the stability of aggregates. Lado and Ben-Hur (2004), found that kaolinitic soils are less dispersive and have high aggregate stability while Montmorillonitic soils are highly dispersive and have poor aggregate stability. In addition, Bu *et al*. (2013) also observed that on black soils containing illite clay mineralogy with stable aggregation, crusting rate tended to be slow.

On the other hand, Lado and Ben-Hur (2004) reported that soils that contain >5% smectite enough to be detected by X-ray, are unstable and highly susceptible to crusting just as smectitic soils. Quartz and feldspar dominated soils are highly dispersive due to minimal ability to bind the particles in the aggregate together (Buhman *et al*. 2006). The surface charges of Quartz and feldspar are close to zero, therefore the aggregate stability of soils which contain these minerals depends on the organic matter (Lado and Ben-Hur 2004).

2.3 Tillage effect on crust formation

Tillage is used to prepare the soil before planting. It involves the use of power to disintegrate and alter the entire topsoil structure. The main aim of tillage is to create suitable soil conditions for the seed, destroy weeds and control pests (FAO 20003b). There are various tillage systems such as conventional tillage, conservation tillage, zero tillage.

Conventional tillage involves the use of mouldboard, discs and chisels and leaves less than 30% crop residues and leaves more than 30% of crop residue. No-till involves no disturbance of the soil and leaves more than 50% of crop residue (Dilallessa 2006). Tillage has a strong effect on soil crusting. This is because tillage disrupts larger aggregates thereby making soil organic matter within aggregates more susceptible to mineralization (Six. 2000). There is a growing interest on the effect of tillage on soil degradation, especially soil crusting due to climate change.

Gicheru *et al*. (2004) compared different tillage systems and reported that minimum tillage creates crusts that are stronger than those in conventional tillage. The reason for stronger crust in minimum tillage was because there was no disturbance of the soil. Similarly, Uson and Poch (2000) reported that reduced tillage resulted in thicker and more complex crusts that consisted of layers with different degrees of sorting and pore type compared to conventional tillage. They also observed that complex and thicker crusts in reduced tillage occurred through a series of events due to slaking or coalescence of aggregates but in conventional tillage the crusts were discontinuous due single event of crusting.

2.4 Conservation agriculture effects on soil crusting

Where intensive tillage is being practiced the organic matter mineralizes rapidly and aggregates are destroyed which leads soil crusting (Laghour *et al*. 2016).
Researchers have been coming up with solutions for the problem of soil crusting. Some researchers have suggested the use of conservation tillage (Limon-Ortega *et al*. 2008, Materechera *et al*. 2007; Nyamadzawo *et al*. 2012; Bhan and Behara 2014), which is suggested to improve soil structure Improved soil structure is proposed to be a solution to the problem of soil crusting (Nyamadzawo *et al*. 2012).

Gicheru *et al*. (2004) found that soils with good aggregate stability with average mean weight diameter ranging from 0.32 to 0.26 mm have 81,2% low chances of soil crusting and losses through runoff and erosion (Levy and Mamedov. 2002; Eltaif and Gharaibeh 2008; Algayer *et al*. 2014; Laghour *et al*. 2016). Sustainable and regenerative processes such as conservation agriculture that conserve and replenish soil organic matter are regarded as an alternative to conventional farming systems (Swanepoel *et al*. 2017). Conservation agriculture refers to a practice in which minimum soil disturbance is achieved. Gicheru *et al*. (2004) noted that the use of crop residues or mulch on soil surface leads to a higher infiltration rate of 70,5 mm h^{-1} compare to infiltration rate of 60,5 mm h^{-1} lower in infiltration rate under conventional, tillage and reduces soil loss from 60% to 10% (FAO 2003a).

Conservation agriculture is also known to provide a natural physical protection against raindrops thereby reducing soil crusting (Laker. 2004; Bhan and Behara 2014). For example, Gicheru *et al*. (2004) found that crusts were formed under minimum tillage with surface mulch. The authors found that crust thickness was 2,30 mm and crust strength was 2,10 kg m^2 while under conventional tillage with surface mulch had 1,96mm crust thickness and crust strength of 2,22 kg m^2.

Conservation agriculture is guided by three principles including, minimal mechanical disturbance, permanent organic soil cover and diversified crop rotations (Bhan and Behara 2014). Conservation agriculture has been reported to lead to improved soil structure therefore minimizing soil crusting (Bhan and Behara 2014). No tillage with management of crop residues on the soil surface results in the slow decomposition at the surface thereby improving soil structure. Surface residues act as mulch that protects the soil from raindrop stress that causes crusting (Laker. 2004; Dahiya *et al*. 2007; Bhan and Behara 2014).

2.5 Soil resilience to structural degradation

Soil resilience is defined as the ability of a soil to recover its function or capacity after stress. Some soils are more stable and have high potential for recovery (Griffiths *et al*. 2000; Zhang *et al*. 2005; Arthur *et al*. 2012). Zhang *et al*. (2005) noted that Ultisol with

45,8% clay content and 5% organic carbon content was resilient to compressive stresses. Similarly, De Andrade Bonetti *et al*. (2017) found that Oxisol with clay content 51,7-55,3% and organic matter of 5,91- 5,94% were more resilient to stress compare to Ultisol with 15,3% clay content and 4,95% of organic matter. Other soils such as sandy loam and a sandy clay loam soil have both poor stability and poor resilience (Gregory *et al*. 2007). Gregory *et al*. (2007) found that sandy loam and a sandy clay loam soil with clay content 14-20% clay were less resilient compared to clay soil with 66% clay. The authors noted that such soils are vulnerable and therefore soil management is most crucial as they are more sensitive (Gregory *et al*. 2007).

Any soil can recover from stress. For example, Lal. (2015) reported that an increase in soil organic carbon from 11 to 15 g kg^{-1} can enhance recovery of soil from stress. Similarly, Arthur *et al*. (2012) found that in soils with similar clay content (16 - 18%), soil which recovers from stress had ≥ 2,1% organic carbon. An influence on stress is imposed by its structure and applied management practices (de Andrade Bonetti et al. 2017). Management practices that prevent the depletion of organic matter promote soil resilience. For example, Arthur et al. (2012) found that soils with 2,1% in organic matter content have greater soil resilience compared to soils with 1,0% in organic matter.

Conservation agriculture enhances the accumulation of crop residue on the soil surface which then improves soil organic matter and soil resilience (de Andrade Bonetti *et al*. 2017). Arthur *et al*. (2012) reported that soils with 2,1% organic matter content are less susceptible to changes in bulk density and or total porosity. Therefore, soils with 2,1% organic matter content are more resilient than soils with 1,0% organic matter content under natural recovery mechanisms (Arthur *et al*. 2012). Similarly, Gregory *et al*. (2009) reported that high organic carbon increases soil resilience to compaction. Gregory *et al*. (2007) found that clay soil is more resilient to stress induced by compaction than sandy loam and sandy clay loam soils. The authors attributed this to the buoyancy effect of pore water pressure on clay soils. De Andrade Bonetti *et al*. (2017) suggested soil resilience is greater in clay soil especially those that are dominated by iron and aluminium oxides. This is because iron and aluminium oxides in clay particles bind the aggregates together and become resistant to crust formation (Mamedov 2006).

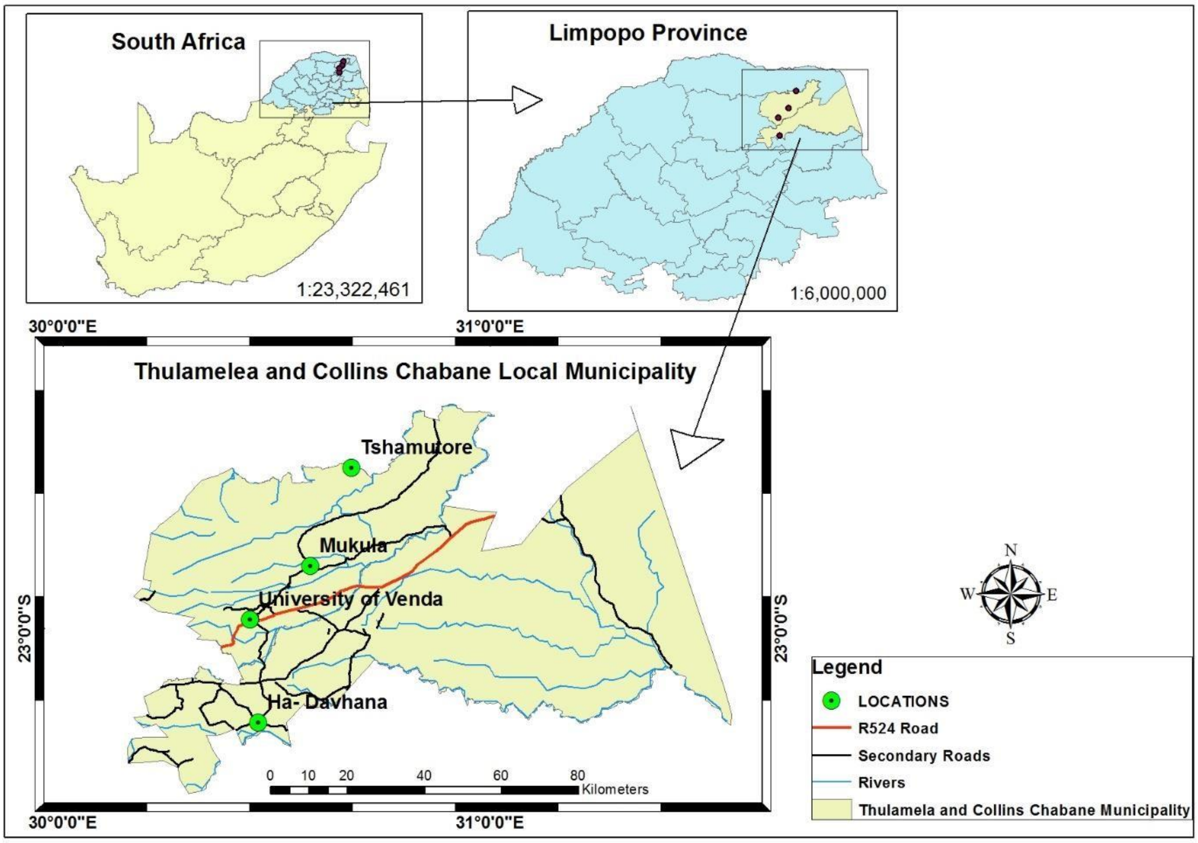
CHAPTER THREE

3.0 MATERIAL AND METHODS

3.1 Sampling sites

The study was carried out at four different sites namely: University of Venda (22°58’ S, 30°26’ E), Mukula (22°37’25" S, 30°35’4" E) , Davhana (23°12’ S, 30°27’36" E) and Tshamutore (23°51’26" S, 30°40’28" E)villages as shown in Figure 1. The sites are situated in Thohoyandou, Limpopo Province of South Africa. They receive a highly seasonal rainfall, about 85% of which falls between October and March (Mzezewa and van Rensburg, 2011). The mean rainfall is approximately 780 mm and the daily temperature varies from 25 °C to 40 °C in summer and ±12 °C to 26 °C in winter. These sites were select due to their differences which include soil types, soil textural classes and mineralogy.

Figure 1: Soil sampling sites


South Africa
1:23,322,461
Limpopo Province
1:6,000,000
30°0'0"E
31°0'0"E
Thulamelea and Collins Chabane Local Municipality
Tshamutore
Mukula
University of Venda
Ha- Davhana
23°0'0"S
23°0'0"S
0 10 20 40 60 80 Kilometers
30°0'0"E
31°0'0"E
N
W
E
S
Legend
LOCATIONS
R524 Road
Secondary Roads
Rivers
Thulamela and Collins Chabane Municipality

3.2 Soils

The experiment was conducted using four soil forms namely, Glenrosa, Hutton, Shortland and Dundee (Soil Taxonomic System for South Africa 1991). The equivalent soil types according to the IUSS Working Group WRB (2015) are given in brackets.

Glenrosa (Leptsols)

This soil form consists of an orthic A horizon overlying a Lithocutanic B horizon. They are shallow and merges into underlying weathering rock

Hutton (Luvisols)

The Hutton soil form consists of an Orthic A horizon and a red apedal B horizon. They occur mostly under the full range of climatic conditions experienced in South Africa and they are red in colour.

Shortland (Ferrosols)

Shortland soil form consists of an Orthic A horizon overlying red structured B horizon, they are structured containing moderate blocky structure in dry state and low in erosion hazard.

Dundee (Fluvisols)

Soil form consists of an orthic a horizon overlying a stratified alluvium. They can be non-red stratified alluvium and red alluvium.

3.3 Soil sampling

Soil samples for characterization were collected using a spade from the four soil forms.

Soil samples were collected randomly from two adjacent fields of approximately 1 hectare each. On all four soil forms, one field was under conventional tillage while the other field was on no-till natural fallow. On each field 20 samples were collected using a spade from 0- 20 cm depth. The samples were then mixed thoroughly to obtain 1 representative soil sample, replicated three times and transferred to plastic bags. Three (3) soil samples were from conventional tillage and the other 3 soil samples were from no- till natural fallow on each soil form giving the total of 24 samples. The samples were taken to the laboratory and air dried to obtain constant weight for 7 days.
After drying the soil samples were sieved using 2mm aperture sieve.

Soil samples were also collected for the pore system analysis. Three (3) soil samples were collected from conventional tillage sites and the other 3 soil samples were collected from no- till natural fallow sites from each soil form. The soil samples were collected using PVC pipes with the length of 20 cm and diameter of 5 cm. On each soil form, the soil profiles were first pre-wetted using tap water to create conditions of soil crusting and to avoid aggregates breakdown while taking samples. The pipes were inserted in the ground by pushing them using a plastic hammer. The pipes were carefully removed by pulling them up by hand. The bottom of each pipes was closed with a cap so that no samples spills from the pipes. All the soils samples which were attached to the outside of the containers were cleaned by rinsing them with tap water and drying using tissue paper. The pipes were then placed in a rigid box and transported to the laboratory. The samples were oven dried for 24hrs at 65℃. This temperature was selected to avoid pipes to melt.

3.4 Soil analysis

Soil texture analysis

Soil texture was determined using hydrometer method described by Bouyoucos (1962). The hydrometer method of silt and clay measurement relies in the effect of particle size on the differential settling velocities within a water column. Using this method (Hydrometer with Bouyoucos scale in g/L), after 40 second all sand-sized particles (0.02 mm and larger) settle out of the suspension and after 4 h, particles larger than clay (0.002 mm) settle out of the suspension. 50 g of 2mm oven-dried soil were weighed in three replicates and transferred into a baffled stirring cup. The cups were half filled with distilled water and 10 ml of sodium hexametaphosphate solution was added. The cups were placed on the stirrer for 10 minutes. The samples were then transferred to the settling cylinder by washing the cup with distilled water. The cylinders were filled with distilled water to the lower mark and allowed to stand overnight. At the beginning of each set sample analysis, temperature was recorded and the hydrometer reading of the blank. Thereafter, a plunger was inserted into suspension, and carefully mixed for 30 sec. The cylinder was placed on a table and the time record. The hydrometer was inserted gently into the suspension and the reading on the hydrometer was recorded at 40 sec. This provided the amount of silt plus clay suspended. After 6 hours, 52 minutes the amount of clay in suspension was recorded using hydrometer. The silt had settled to the bottom of the cylinder by this time. The percentage clay, silt and sand were then calculated as follows:

$$\text{clay } (\%) = \frac{\text{hydrometer reading at 6 hrs,52 minutes}}{\text{mass of sample}} \times 100 \qquad [1]$$

$$\text{silt } (\%) = \frac{\text{hydrometer reading at 40 seconds}}{(\text{mass of sample} - \%\ \text{clay})} \times 100 \qquad [2]$$

$$\text{sand } (\%) = 100\% - \%\ \text{silt} - \%\ \text{clay} \qquad [3]$$

Organic carbon analysis

Soil organic carbon was determined using Walkley and Black method (Nelson and Sommers, 1982). This procedure involves reduction of potassium dichromate by organic carbon compounds and subsequent determination of the unreduced dichromate by oxidation-reduction titration with ferrous ammonium sulfate. 1 g of soil sample was weighed into a 500 ml conical flask. 10 ml of potassium dichromate solution was transferred into the flask with using a Pipette. 20 ml of concentrated sulphuric acid was then added using the measuring cylinder. The flasks were swirled carefully and allowed to stand for 30 minutes. 250 ml of water and 10 ml phosphoric acid was added using a measuring cylinder and allowed to cool. The two blanks containing all reagents, but no soil was prepared the same way as the soil suspensions.1 ml of the indicator-solution was added, and the sample titrated with ferrous sulphate while stirring using a magnetic stirrer. The colour changed from brown to purple to blue and finally to green.

Organic carbon percentage was then calculated as (Volume of ferrous ammonium sulfate solution required to titrate the blank minus Volume of ferrous ammonium sulfate solution required to titrate the sample multiplied by 0,3 ($3 \times 10^{-3} \times 100$, where 3 is the equivalent weight of Carbon) divided by mass of air dry soil.

Clay mineralogy analysis

soil mineralogy was determined using the Rietveld method (Zabala *et al*. 2007). The determination of the types and relative amounts of the minerals present in soil (soil mineralogy) is determined routinely because of its strong influence on soil behaviour. X-ray diffraction is the most powerful technique used for analysis of minerals and offers mineral phase's identification and quantification. This analysis provides information about the clay minerals present in a sample and the abundance. Clay fraction is routinely used as a fingerprint identification technique of various solid materials in the laboratory. It is a high-tech, rapid and cheap technique for qualitative and quantitative analysis of crystalline compounds; when X-rays interact with oriented aggregate mounts of clay mineral particles that are prepared by the filter-peel technique, a diffraction pattern called a diffractogram is produced and can be quantified. Information obtained from this pattern shows the extent of d-spacing expansion and or the contraction indicative of certain clay minerals during subsequent treatments (Air drying, glycolation with ethylene glycol, heating to 300°), the information obtained give types of clay minerals by revealing changes in crystal structure spacing or loss of the structure.

About 10 g of 2mm air dry sample was suspended 500 ml of water in a 500 ml beaker. Dispersion was done using a sonic probe for 5 minutes, then transferred into a 1 L measuring cylinder and filled to the 20 cm mark with deionized water. The samples were soaked overnight to allow material to settle. According to Stuart's law spherical particles will settle faster below the 5 cm mark while the clay particles which are platy and less than 2 µm in size will remain suspended between the 5 and 20 cm mark. Using a siphon tube, the suspension was collected from above the 5 cm mark of the measuring cylinder and transfer into a 500 ml bottle for storage. Oriented aggregate mounts were prepared by the filter-peel technique using a filtration system setup. Oriented aggregate mounts were placed on the shelf of desiccator. The sample was placed onto a holder into the sample position of the stage. The sample was placed back into the sample measurement position by pulling up the spherical handle of the stage and slide down the instrument door. The door handle was press down with force in order to close it correctly. Measurement parameters were activated for a typical Lynx eye. Then start button was activated to initiate acquisition.

Aggregate stability measurements

Soil aggregate stability was determined using wet sieving method by Le Bissonnais (1996). Soil aggregate stability was measured in triplicate using the wet sieving procedure described by Eijkelkamp Agrisearch Equipment (Art no: 08.13). The wet sieving instrument consists of a sieve holder with 8 sieves of 0.25 mm. It has two holes (build-in stop) on the shaft with one on the top position of the other with distinct functions. The top hole allows water to leak after sieving while the bottom hole is responsible for allowing sieving into the filled cans.

4.0 g sample of air-dried 2 mm aggregates were weighed and transferred into a 0.25 mm sieve. The aggregates were pre-moistened then left for approximately 10 minutes before submerging them into the water-filled cans. The reason to pre-moisten aggregates was to prevent slaking when the sieve was submersed into the water filled can. Then the sieves were placed in the sieve holder. Below the sieves, weighed and marked cans were placed. The cans were filled with enough distilled water to cover the soil aggregate during sieving. Thereafter, the sieve holder was placed in the second hole on the instrument shaft. Sieves were moved up and down in the distilled water by switching on the motor for 3 minutes. After three minutes the motor automatically stopped then the sieve holder was uplifted and placed in the top hole on the instrument shaft to allow water to leak from the sieves. When water stopped leaking, the cans were replaced with another set of marked cans and then sufficiently filled with dispersing solution of 2 g L^{-1} sodium hexametaphosphate.

The sieve holder was then placed again in the second hole on the instrument shaft. Sieves were again moved up and down in the dispersing solution by switching on the motor into the continue position until sand particles remain on the sieve. Thereafter, cans were dried in an oven at 110 °C for 24 h to obtain a constant weight. The aggregate stability was given as the mass of soil obtained in the dispersing solution cans divided by the sum of the masses obtained in the dispersing solution cans plus distilled water cans.

3.5 Miro X-ray computed tomography scanning and image analysis

Three soil samples from each representative sample were scanned with XμCT at MIXRAD facility section of The South African Nuclear Energy Corporation SOC Limited (Necsa). Thus, a total number of 12 samples were scanned per treatment.
The samples were scanned using a Nikon XTH 225L micro-focus CT X-ray unit (Nikon Metrology, Leuven, Belgium), located at the MIXRAD laboratory at the South African Nuclear Energy Corporation, Pelindaba. Scanning parameters were set to 90keV/90μA to optimise penetration of X-rays through the soil aggregates. The scanning resolution was set at 18.9 μm in order to visualise the soil microstructure. An aluminium filter was used to approximate a homogeneous X-ray beam spectrum of high Xray photons by removing the lower energy photons that contributes to noise.

The X-ray machine acquires a shading correction image that is used to calibrate the background of the acquired radiographs. The samples were securely mounted in a polystyrene mould to avoid any movement during each scan. The mounted specimens were then placed on to a rotating sample manipulator, which facilitated scanning at 360℃. One thousand projection images were obtained in the 360℃ at 2 sec exposure time for each projection. The scans were then reconstructed using Nikon CTPro software® (Nikon Metrology, Leuven, Belgium) and further analysed using VGStudio Max V3.0® (Volume Graphics GmbH, Heidelberg, Germany).

To avoid the edge effects, a region of interest of 52 0.1mm^3 volume was selected at the middle of the 3D sample. 3D total porosity was defined as the total number of pore voxels divided by the total number of volume voxels (Ferro *et al*. 2014).

3.6 Soil resilience

The soil resilience index will be calculated using Equation 1 (Herrick and Wander 1998).

$$\mathrm{Res} = \frac{X_{CA} - X_{CT}}{X_{CT}} \qquad [5]$$

Where;
Res = Resilience
X = the soil physical attribute.
CA = the magnitude of the physical attribute in conservation agriculture.
CT = the magnitude of the physical attribute in conventional tillage.

3.7 Data analysis

The scans were reconstructed using Nikon CTPro software® (Nikon Metrology, Leuven, Belgium) and further analysed using VGStudio Max V3.0® (Volume Graphics GmbH, Heidelberg, Germany). Analysis of variance (ANOVA) was performed using statistix10.1. Mean separations were done using Fisher's protected least significant differences (LSD) at $P < 0,05$

CHAPTER FOUR

4.0 RESULTS

4.1 Soil chemical, physical and mineralogical properties

Some physical, chemical and mineralogical properties of the soils used in this study are shown in Table 1. The textural classes include clay, clay loam, sand and sandy loam (Table 1). The most dominant clay minerals were quartz and kaolinite (Table 1). The values of organic content were 0,85%, 1,1%, 0,5%, 0,5% on Ferrosols, Luvisols, Fluvisols and Leptsols soils respectively. These organic matter contents were statistically similar. Aggregate stability was significantly different among soils. Aggregate stability of Ferrosols was 57,5%, 69,5% in Luvisols, 32,7% in Leptsols and 14,2% in Fluvisols.

Table 1: Selected physical, chemical and mineralogical properties for the 4 soil forms

Soil form	PSD (%)			Textural class	AS (%)	OC (%)	Q	H	A	K	MC	PC	AN	T	S
	Sand	Clay	Silt												
Hutton (Luvisols)	13,1	73,3	13,0	Clay	57,5b	0,9a	22,7	8,2	1,4	67,8	0	0	0	0	0
Shortland (Ferrosols)	35,6	39,3	25,3	Clay loam	69,5a	1,1a	25,9	3,4	1,1	65,3	0,1	0,6	0	0	3,8
Dundee (Fluvisols)	89,7	8,2	2,1	Sand	32,7c	0,5a	98,4	0,4	0	1,4	0	0	0	0	0
Glenrosa (Leptsols)	74,3	14,3	11,4	Sandy loam	14,2d	0,5a	40,9	0	0	0	24,0	31,5	3,4	0,3	0

AS=Aggregate stability OC=Organic carbon (Different letters in a column indicate significant differences among soils, P<0.05) Q= Quartz H= Hematite A= Anatase K= Kaolinite MC= Microcline PG= Plagioclase AN=Actinolite T= Talc S= Smectite

4.2 Effect of crusting soil on total porosity

The results for total porosity on all soil types were significant ($p<0.05$). The values for total porosity of Ferrosols and Luvisols soils were statistically similar, however, total porosity values for Leptsols and Fluvisols were statistically different (Figure 2). Total porosity for Ferrosols, Luvisols, Leptsols and Fluvisols were in the order of 34,3 %> 32,2% >23,5% >16,3% respectively. High porosity was found on Ferrosols soils (34,3%), while the least porosity was found on Leptsols soils (16,3%).

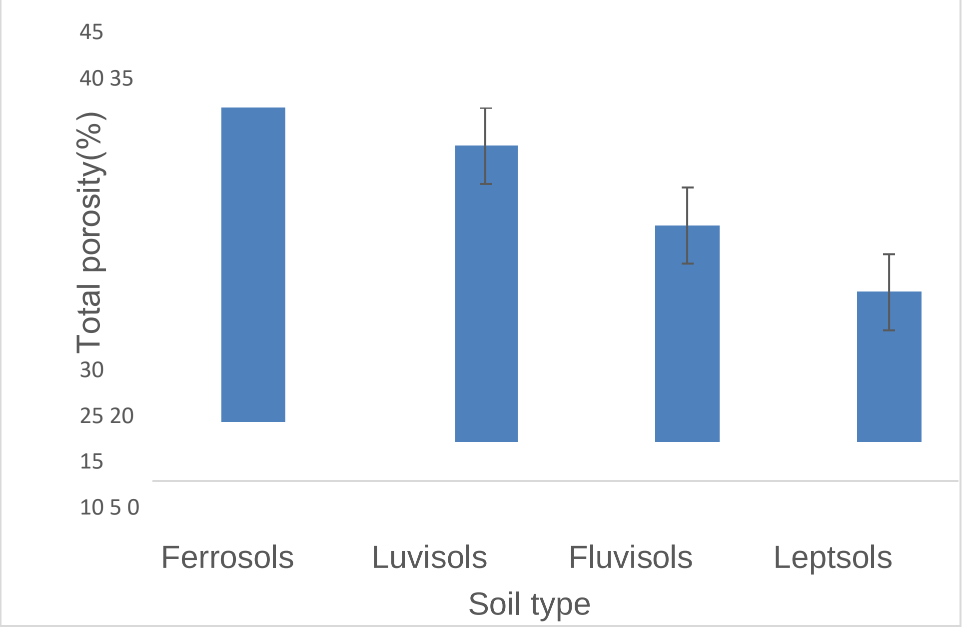


Figure 2: Effect of soil type of total porosity. Error bars represent standard error

4.3 Effect of tillage on total porosity on crusting soil

There was no significant difference on total porosity between the two tillage practices (p<0,05) However, higher total porosity was observed under conservation agriculture as compared to conventional tillage (Figure 3). Total porosity on conservation agriculture was 28,4% and under conventional tillage was 24,7%. (Figure 3).

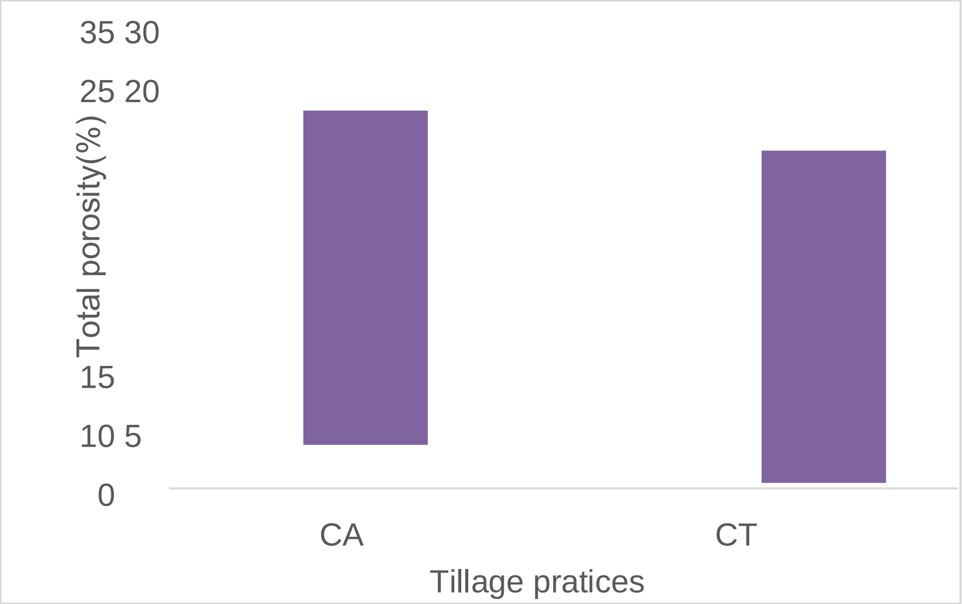


Figure 3: Effect of tillage practices on total porosity: CA= Conservation agriculture CT= conventional tillage. Error bars represent standard error

There was interaction between soil type and tillage of on total porosity. Total porosity was 39,7% higher on Shortland soil under conversation agriculture conditions and 14,1% lower on Leptsols soils under conversation agriculture (Figure 4). There was significant difference in total porosity on Ferrosols under both conservation agriculture and conventional tillage. Total porosity was statistically similar in Luvisols under both conservation agriculture and conventional tillage. Total porosity of Leptsols and Fluvisols under both conventional tillage and conservation agriculture were statistically similar (Figure 4).

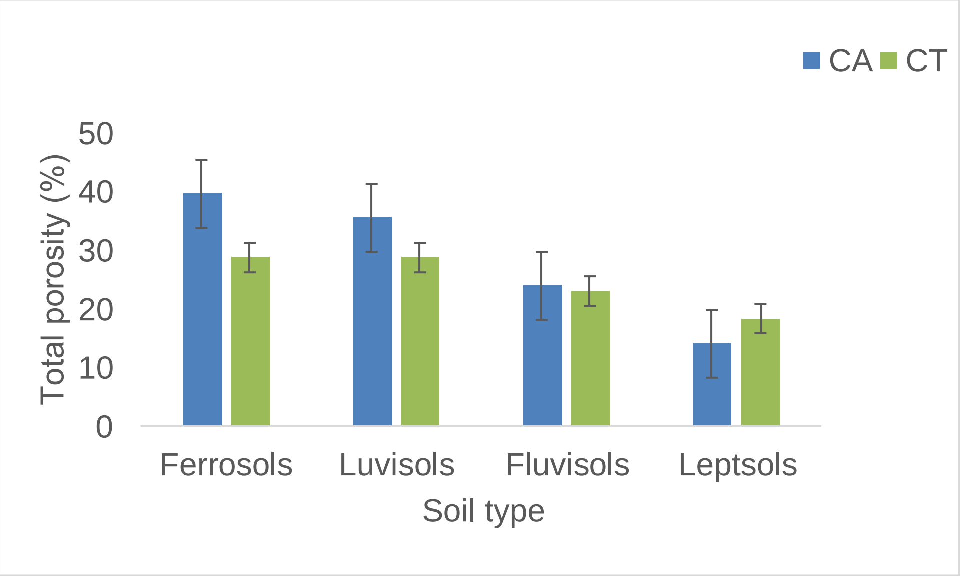


Figure 4: Effect of tillage on total porosity of different soil type. CA= Conservation agriculture CT= conventional tillage. Error bars represent standard error

4.4 Effect of soil aggregate stability and organic carbon content on total porosity in crusting soil

The results for aggregate stability were significant at ($p<0.05$) as influenced by both soil types and tillage (Table1). All soil types had significant results for aggregate stability. Aggregate stability for Ferrosols soils and Luvisols soils were statistically similar (Table 1) however, greater aggregate stability was noted in Ferrosols soils with a value of 57,5% as compared to 32,7% in Leptsols soils (Table 1). The results were statistically different between the two tillage practices. Aggregate stability was 47,5% higher under conservation tillage as compared to 35,9% under conventional tillage (Figure 5).

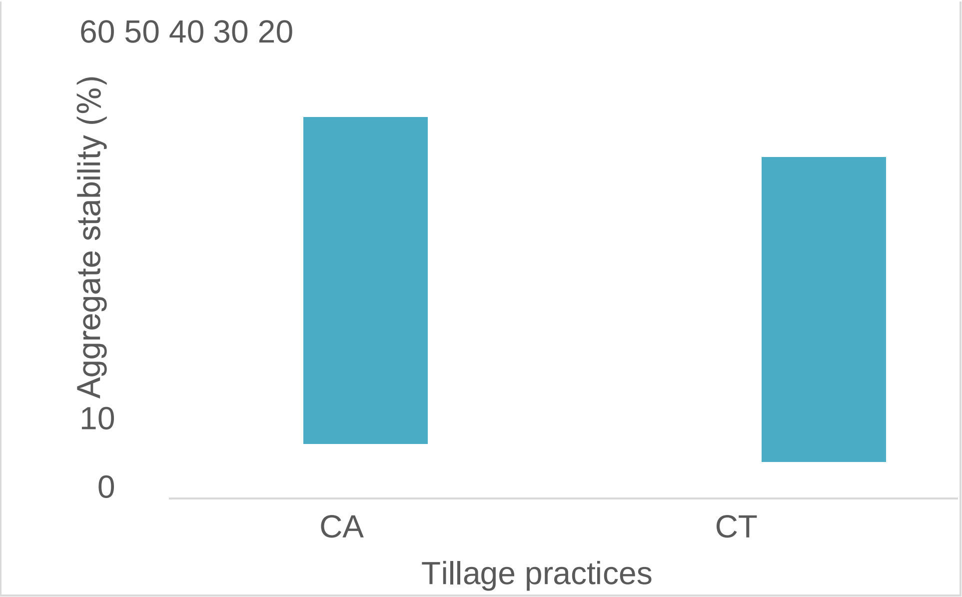


Figure 5: Effect of tillage on aggregate stability. CA= Conservation agriculture CT= conventional tillage. Error bars represent standard error

The results for organic carbon were not significant at (p<0.05) in all soil types under both conservation tillage and conventional tillage. Organic carbon on all soil types were statistically similar (Table 1). however, organic carbon was 1,1% higher on Ferrosols soil and 0,5% lower on Leptsols soil and Fluvisols soil as they had similar value. There was no significant difference for organic carbon content on both tillage practices (Figure 6). 0,8% higher on organic carbon was found on conservation agriculture and 0,7% lower on conventional tillage (Figure 6).

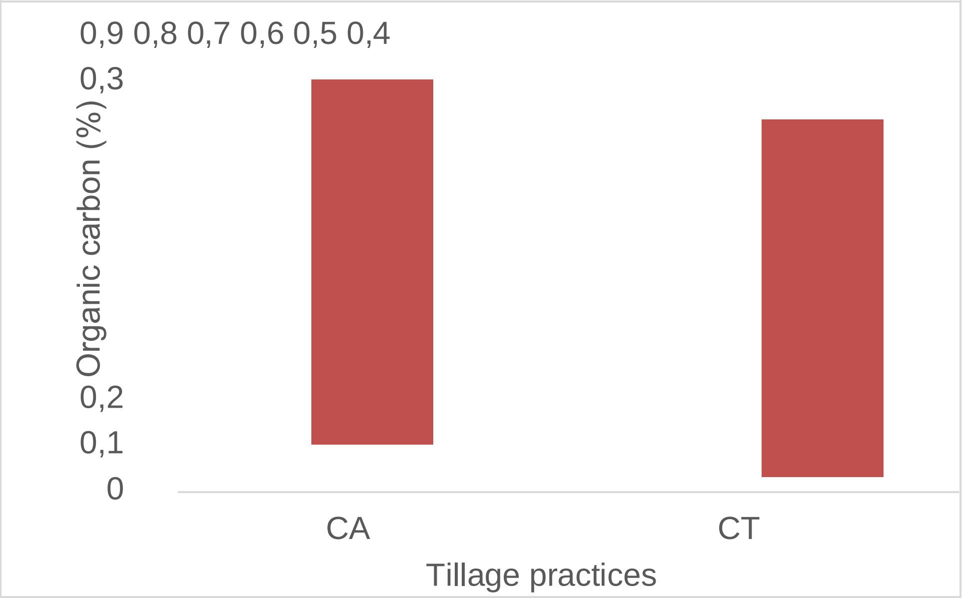


Figure 6: Effect of tillage on organic carbon. CA= Conservation agriculture CT= conventional tillage. Error bars represent standard error

4.5 Soil resilience on different soil type

Soil resilience was in the order of 37,5> 23,9> 4,1> -30,1 in Ferrosols, Luvisols, Fluvisols and Leptsols respectively (Figure 7). Soil resilience increased on Ferrosols and Luvisols, lower in Fluvisols and Leptsols soils and negative (-30,1%) in Leptsols soil.

Luvisols, Ferrosols and Leptsols soils showed resilience ability to crusting under conservation agriculture. However, Fluvisols soils showed resilience to crusting can be achieved under conventional tillage.

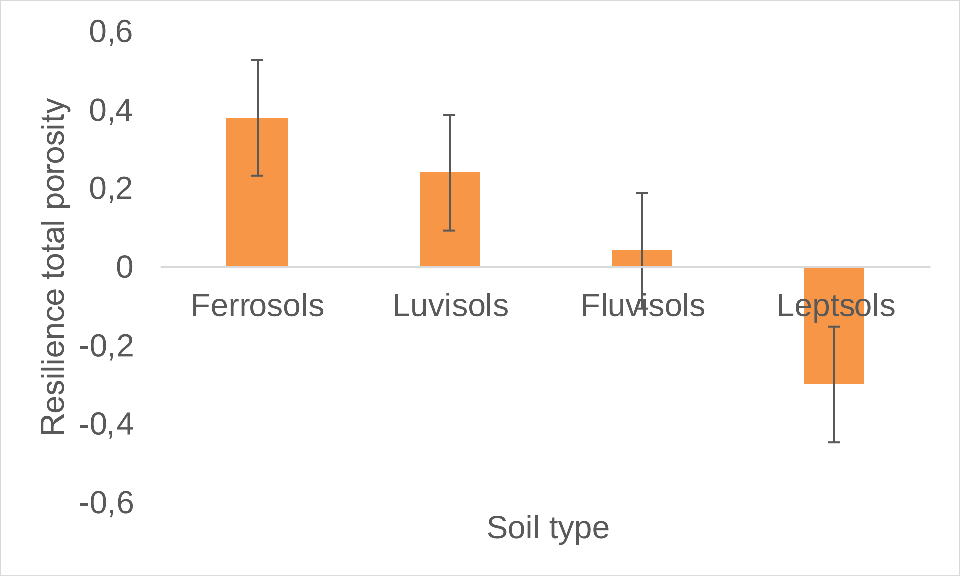


Figure 7: Soil resilience in different soil

4.6 Relationship between aggregate stability, clay content and organic carbon on soil resilience

There was a positive linear relationship between clay content and resilience of total porosity (Figure 8). Soil resilience increased as soil organic carbon increased (Figure 9). Soil resilience increased as aggregate stability increased (Figure 11)

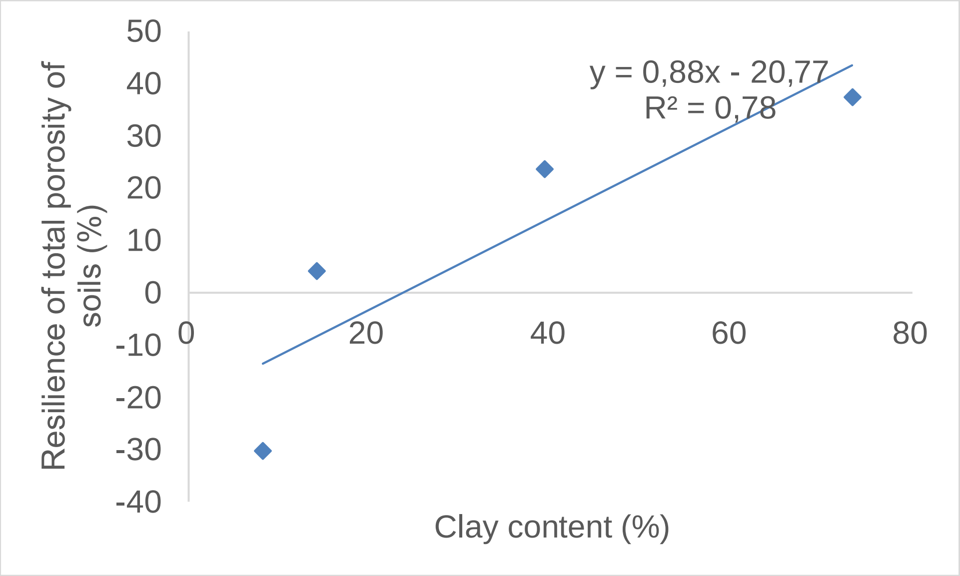


Figure 8: Relationship between soil resilience and clay content

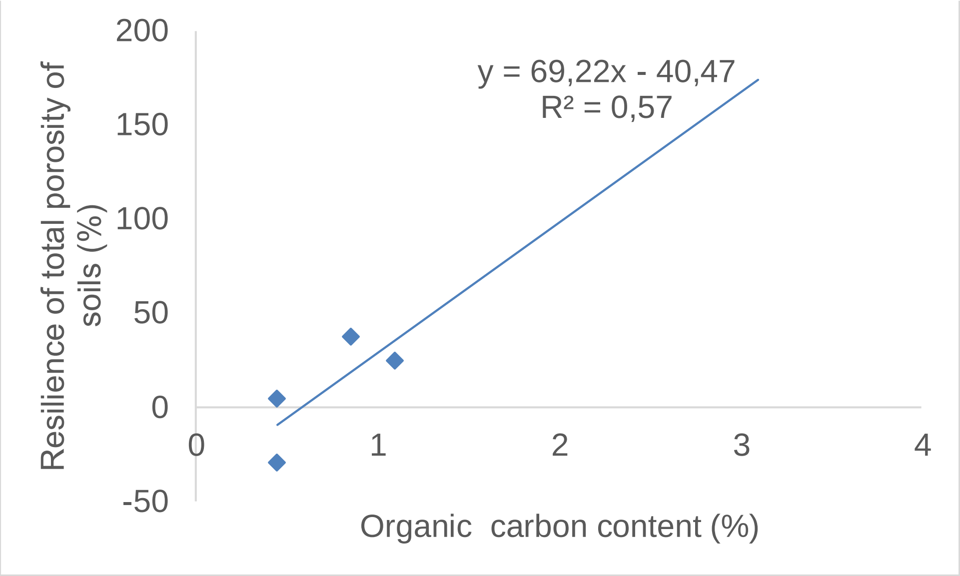


Figure 9: Relationship between soil resilience and organic carbon content

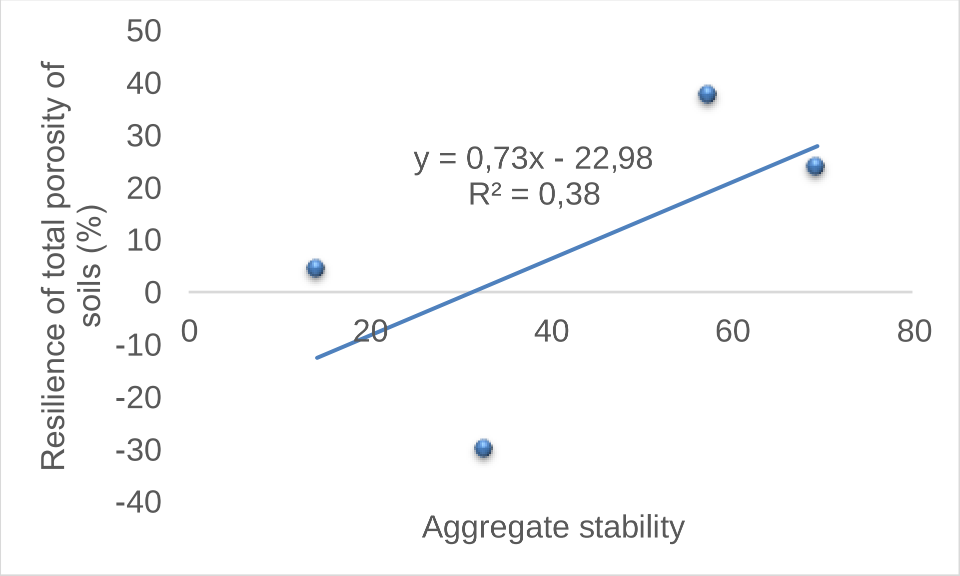


Figure 10: Relationship between resilience total porosity and aggregate stability

4.7 Micro X-ray computed tomography images of vertical sections of soil surfaces

X- ray micro focus computed tomography was used to visualize crust formed on soils (Figure 11). The present of crust layer on Shortland, Hutton and Glenrosa soils were clearly visible especially under conventional tillage (Figure 11). Dundee soil did not have any visible crusts under both conventional tillage and conservation tillage.

Moreover, there was also no visible soil crust in all soils under conservation agriculture. Cracks were also observed in Shortland and Hutton soils (Figure 11). Cracks were also observed in Shortland and Hutton soils both conventional tillage and conservation tillage (Figure 11).

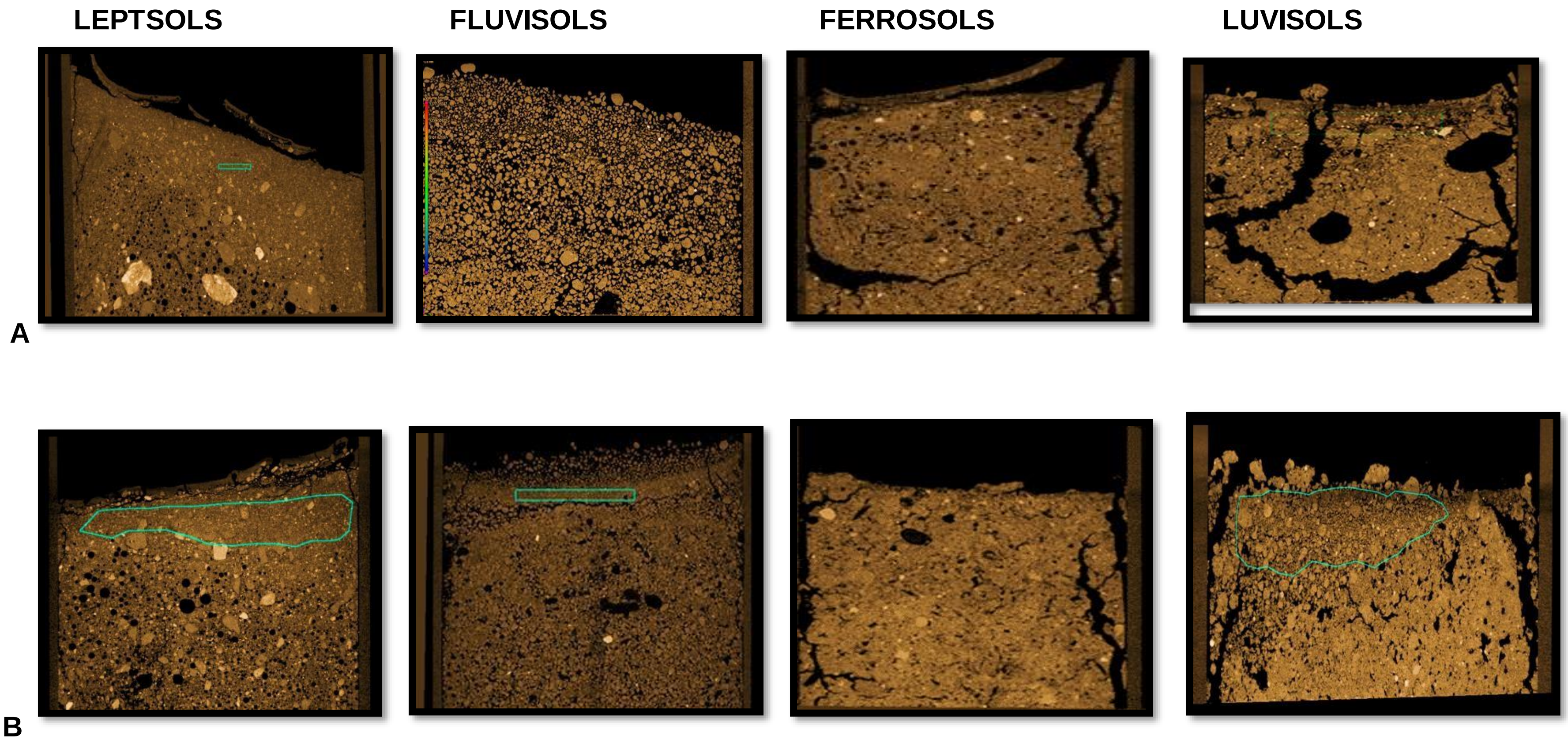


Figure 11: Micro X-ray computed tomography images of vertical sections of soil surfaces (A) typical crusted soil surface under conventional tillage (B) typical crusted soil surface under conservartion agriculture.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Soil structure degradation and crust formation

The presence of crust layer on Ferrosols, Luvisols and Leptsols soils were clearly visible (Figure 11). A thin compacted layer was present on the topsoil layer on studied soils. However, no crusts were observed on Fluvisols soils. Crust formed on the top layer on the soils influenced total porosity. Aggregate stability was in the order of 69,5%>57,5%>32,7%>14,2% on Ferrosols, Luvisols, Fluvisols and Leptsols respectively (Table 1). Ferrosols and Luvisols had more stable aggregate stability as compared to Fluvisols soil which may have contributed to resistant to aggregate breakdown by slacking. Similar observation was reported by Levy and Mamedov. (2002), who observed that highly aggregated soil has high tendency to resist aggregate breakdown and are less likely to form crusts. Belnap. (2001) found that soils that are susceptible to crusting have poor aggregate stability. Moreover, Gicheru *et al*. (2004) found that soil with aggregate stability of 32%-37% were most stable and less susceptible to crust formation compare to soil with aggregate stability <7%.

Total porosity was in order of 34,3%>32,2%>23,5%>16,3% for Ferrrosols, Luvisols, Fluvisols and leptsols respectively. Lower porosity on Fluvisols and Leptsols soil may have caused by crust formation due to poor aggregate stability on these soils compared to Ferrosols and Luvisols soils. Similarly, Miriti *et al*. (2013) conducted a study on sandy loam soils and reported that porosity was higher at 47,04% on noncrusted soil compared to 43,14% on crusted soils.

5.2 Crust formation in different soils

Total porosity was influenced by soil type. Total porosity increases from 16,3 to 34,3 % (Figure 2) as clay content increased (table 1). Ferrosols and Luvisols soil had 39,33 to 73,33% higher clay content compared to Fluvisols and Leptsols soil. Clay content reduces susceptibility to aggregate breakdown by binding particles together. This was observed on the study conducted by Mamedov (2006), in which the author reported that an increase in clay content reduces aggregate breakdown because clay particles bind aggregates together contributing to cohesive strength of the aggregates. Moreover (Fox *et al*. 2004; Gicheru *et al*. 2004) found that soil which contain high sand content and silt are most likely to form crusts. Therefore, 74,31 to 89,67% increase in sand in Fluvisols and Leptsols soil may have cause this soil to be less stable. Valentin (2005) also observed that in sandy soils crusts form where silt+ clay content exceeds 5% and most severe crusting observed for silt+ clay of 10%.

Soil mineralogy was also a contributing factor to stability of aggregates. Ferrosols and Luvisols soil were dominated by kaolinite. Aggregate stability was in order of 69,5%>57,5>32,7%>14,2% on Ferrosols, Luvisols, Fluvisols and Leptsols, respectively (Table 1). Ferrosols and Luvisols soils were more stable compared to Fluvisols and Leptsols soils. This may be due to dominance of kaolinite which are more stable mineral. Similarly, Lado and Ben-Hur (2004) reported that soils dominated by kaolinitic mineral are more stable. Therefore, Ferrosols and Luvisols soils were more stable thus caused less crust to form which was insignificant to reduce total porosity. Ferrosols soil contained 3,8% of smectite. The presence of smectite is considered to make soil unstable. However, Lado and Ben-Hur (2004) reported that soil which contain smectite (>5%) most likely to be unstable and more susceptible to form crusts. Therefore, Ferrosols soils contained only 3,8% of smectite and hence was less unstable.

On the other hand, Leptsols and Fluvisols soils were dominated by Quartz with the value of 41% and 98%, respectively. Aggregate stability of Leptsols and Fluvisols soils were lower by 32,7% and 14,2%, respectively. The presence of this mineral causes soil to be unstable and lead to the severe crust formation. Total porosity of Leptsols and Fluvisols soil was 16,3% and 23,5% lower, respectively (Figure 2) compared to Ferrosols and Luvisols soils. Similarly, Buhman *et al*. (2006) reported that the presence of Quartz causes the soil to be unstable. The authors attributed this to inability to bind the aggregate particles together. Lado and Ben-Hur (2004) found that the surface charges of Quartz are close to zero, therefore the aggregate stability of soils which contain these minerals depends on the organic matter content.

However, in this study Fluvisols and Leptsols soils were dominated by quartz and were unstable. Moreover, soil organic carbon in Fluvisols and Leptsols soils were insignificant and had the similar amount of 0,5%. Chenu *et al*. (2000) found that organic matter >2,0% leads to formation of macroaggregates which are resistant to disruptive forces such as slaking.

5.2 Tillage effect on crust formation

Tillage had an influence on total porosity. Total porosity for both conservation agriculture and conventional tillage were statistically similar. However, total porosity on conservation agriculture was higher (28,4%) compared to conventional tillage was 24,8% lower (Figure 4). This implies that total porosity improved on conservation agriculture compare to conventional tillage. Six *et al*. (2000) found that conventional tillage mechanically breaks down macroaggregates into microaggregates. Igwe and Obalum (2013) reported that microaggregates breakdown through dispersion results in finer particles and consequently lead to soil crust formation during rainfall or slacking imposed by rapid intake of water. In addition, Materechera (2009) concluded that the application of organic amendments increases the soil organic matter which results in the formation of macroaggregates resistant to slaking. In this study organic carbon content was 0,8% under conservation agriculture and 0,7% under conventional agriculture (Figure 6). This amount was low to improve soil aggregation especially macroaagregate. Chenu *et al*. (2000) found that organic matter >2,0% leads to formation of macroaggregates which are resistant to slaking (Materechera 2009).

Aggregate stability under conservation agriculture was 47,5% compared to 39,5 % under conventional tillage (Figure 5). This shows that there was less transition to improved total porosity. (Bhan and Behara (2014); Gicheru *et al*. (2004) found that more severe crusts were formed under conventional tillage and less crusts were formed on conservation agriculture. In contrast, Uson and Poch (2000) reported that reduced tillage resulted in thicker and more complex crusts that consisted of layers with different degrees of sorting and pore type compared to conventional tillage. These contradicting results may be due to different soil types, rainfall intensity and other factors used in the study.

5.3 Soil resilience to structural degradation

Resilience of total porosity was in order of 37,5%>23,9%>4,1%>-30,1% in Ferrosols, Luvisols, Fluvisols and Leptsols, respectively (Figure 7). There was a positive linear relationship between resilience of total porosity and clay content (Figure 8). Clay content may have contributed to increasing resilience of total porosity. This was the case in many studies such as (Gregory *et al*. (2009), De Andrade Bonetti *et al*. (2017). The authors reported that soil resilience is higher in soils with more clay content. This is because clay soils increase soil aggregation thereby developing a stable soil structure (Gregory *et al*. 2007). Clay particles bind the aggregates together and becomes resistant to crust formation (Mamedov 2006) hence, improving resilience of total soil porosity. Moreover, De Andrade Bonetti *et al*. (2017), also observed that clay soils have high capacity to self-organize after disturbance for example, after crust formation.

There was also a positive linear relationship between resilience of total porosity and soil organic carbon (Figure 9). Soil organic carbon may have caused the soil to be more resilience. Similar results were found in several other studies (Griffiths *et al*. 2000; Zhang *et al*. 2005; Kuan *et al*. 2007 and Gregory 2009) in which the authors observed that soil resilience increases with increase in soil organic carbon. This is because organic matter acts as a binding agent between soil particles. Soil organic matter also reduces clay wetting which prevent aggregate breakdown to form crusts (Blanco-Canqui and Lal 2004). It also acts as a secondary particle to form stable aggregate (Blanco-Canqui and Lal 2004; Al-Kaisi and Yin 2005). Soil organic matter increases cohesion between mineral particles leading to improved aggregates and soil structure (Laghour *et al*. 2016).

Tillage practices have also influenced the resilience of all the soils. Resilience of total porosity had a positive value for Luvisols, Ferrosols and Fluvisols which may indicate that the resilience in these soils can be achieved through conservation agriculture. On the other hand, resilience of total porosity on Leptsols soil was negative value (-30,1%) which may indicate that the resilience in these soils can be achieved through conventional tillage.

Many studies found that resilience is high under conservation agriculture than in conventional tillage (Griffiths *et al*. 2000; Kuan *et al*. 2007, Gregory *et al*. 2009, Arthur *et al*. 2012, de Andrade Bonetti *et al*. 2017). Most studies were done on soils with high clay content and they found that resilience is high under conservation agriculture. However, Arthur *et al*. (2012) conducted a study on sandy soils with similar clay content but different soil organic carbon. In their study, the authors found that resilience was high in soil which contained high organic carbon and lower in soil with lower organic carbon.

A Similar trend was noted in this study, although Fluvisols and Leptsols soil had similar soil organic carbon content value (0,5%) their resilience was (4,1 and -30,1%) lower, respectively. Resilience of total porosity increased as aggregate stability increases (figure 10). A clear trend may be noted that clay content of 73% and 39%) on Luvisols and Ferrosols soil and organic carbon content of (0,9% and 1,1%) respectively, under conservation agriculture promotes soil aggregation and stable structure which increase resilience after disturbance (Griffiths *et al*. 2000, Kuan *et al*. 2007, Gregory *et al*. 2009, Arthur *et al*. 2012, de Andrade Bonetti *et al*. 2017) However, conventional tillage disrupt soil aggregates and expose the soil organic matter to rapid decomposition (Al-Kaisi and Yin 2005) which leads to less resilience.

CONCLUSION AND RECOMMENDATIONS

Soil type influenced crust formation of the studied soils. Luvisols and Ferrosol soils were more stable as compared to Fluvisols and Leptsols. The dominance of kaolinitic mineral influenced these soils to be more stable. While the presence of quartz in

Fluvisols and Leptsols soils have caused them to be less stable. Organic carbon content also had significant influence on aggregate stability of the soils. Higher organic carbon content was noted in Luvisols and Ferrosols while, Fluvisols and Leptsols had lower organic content. Total porosity was higher in Luvisols and ferrosols. Fluvisols and Leptsols soils had lower total porosity. Total porosity was influenced by crust formation in all soils. Tillage practices promoted crusting especially on sandy soils and reduced total porosity. However total porosity increased under conservation agriculture. Soil resilience increases with increased in clay and organic carbon content. The combination of these factors contributed to soil aggregation and their resilience after disturbance. Therefore, conservation tillage in combination with mulching or organic matter application is required to enhance soil resilience. There is therefore a need to determine the threshold level of organic carbon and clay content in which significant soil resilience can be achieved.

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