VISUAL ASSESSMENT OF STRUCTURE OF CLAYEY SOILS UNDER LONG-TERM NO-TILLAGE IN THOHOYANDOU, SOUTH AFRICA.

By

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THESIS
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DECLARATION

I declare that the thesis hereby submitted to the University of Limpopo, for the degree of Doctor of Philosophy in Agriculture (Soil Science) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged.

Kopano Conferance Phefadu **18 February 2024**

Full names **Date**

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DEDICATION

I dedicate this Ph.D. to my wife and kids.

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LIST OF ACRONYMS AND ABBREVIATIONS

BD	Bulk density
cm	Centimeter
CT	Conventional tillage
cm/min	Centimeters per minute
°C	Degree Celsius
EC	Electrical conductivity
g/cm^3	Grams per cubic centimeters
LT	Long-term
MWD	Mean weight diameter
mg/m^2/min	Milligram per square meter per minute
mm	Millimetres
mS/cm	Millisiemens per centimeter
NT	No-tillage
OC	Organic carbon
%	Percent
pH(KCl)	pH in potassium chloride
pH(W)	pH in water
LS	Short-term
SOC	Soil organic carbon
m^2	Square meter
Sq	Structure quality
Ssq	Subsoil structure quality
SubVESS	Subsoil visual evaluation of soil structure
VG	Virgin field
VESS	Visual evaluation of soil structure
V%	Volume percentage

PUBLICATIONS DURING CANDIDATURE

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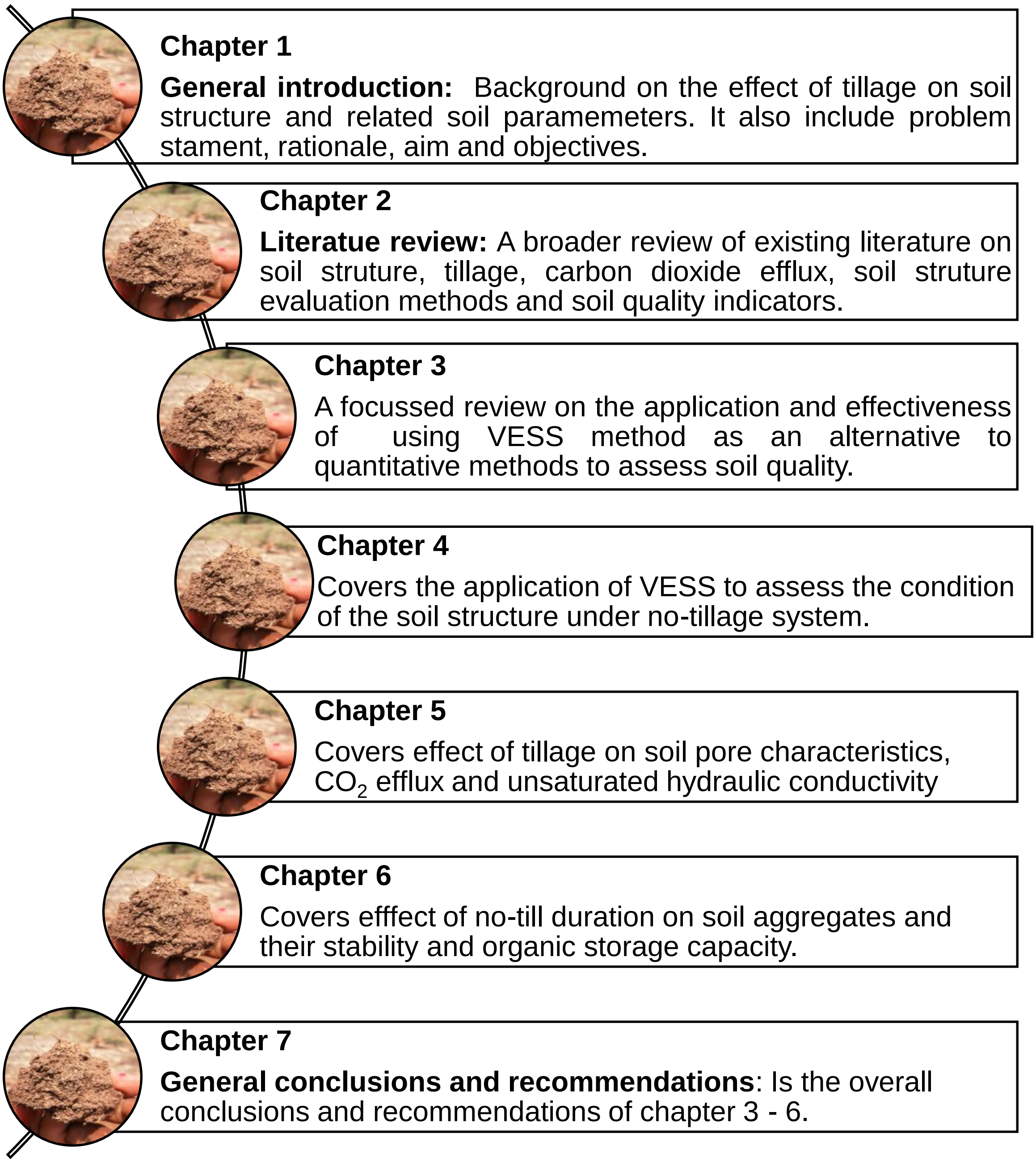
Articles in preparation from the thesis

1. The use of visual evaluation of soil structure (VESS) method to assess soil quality: Review.
2. Pore characteristics, CO_2 efflux and unsaturated hydraulic conductivity of soils under long term no-tillage system.
3. Assessing the impact of tillage duration on soil aggregate size distribution, stability and aggregate associated carbon.

THESIS STRUCTURE



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ABSTRACT

Soil structure is described as a complex and dynamic soil property, partly related to inherent characteristics of particle size and clay mineralogy and also anthropogenic influences related to land use and management. Tillage management systems influence several soil structural properties such as reduced pore volume and size due to compaction, which on the other hand may affect the soil-water and air relation. Soil structure is regarded as one of the key soil quality indicators, thus, its evaluation and monitoring should be emphasized in soil management and conservation. Soil quality is generally based on the approaches that focuses on the inherent soil properties or human management effects. Soil quality is strongly linked to soil structure, because poor quality soil structure may lead to problems such as susceptibility to compaction, erosion and desertification.

Visual soil structure quality methods for soil quality assessment such as visual evaluation of soil structure (VESS) are effective for controlling and monitoring the soil functions for sustainable agriculture. VESS is a cheap and simple field evaluation method which is used to rate soil structure quality based on related parameters such as size and appearance of aggregates, visible porosity, and roots. Qualitative measurements of related parameters like pore characteristics, aggregate stability, aggregate size distribution, bulk density, organic carbon and unsaturated hydraulic conductivity were done to validate the outcome of VESS and effect of tillage. Tillage has a direct effect on the transformation of soil structure. The impacts of the duration of no-tillage (NT) are still not yet well elucidated especially on clayey soils.

The aim of the study was to visually assess the structure dynamics of the soils with relatively high clay content and profiling related structural parameters, under long term no-tillage systems in a subtropical climate. The study was carried out in Tshivhilwi and Dzingahe, Thohoyandou, Vhembe district, Limpopo Province, South Africa. The no-tillage fields in Tshivhilwi and Dzingahe were 8 years (short-term) and >40 years (long-term) respectively. Soil samples were collected and field measurements of the related parameters were done in three fields in each study area, namely: no-tillage, conventional tillage and virgin field. Five sampling points were randomly selected in a portion (area = 1000 m^2) of each field per location considering the homogeneity of the soil. Soil sampling depths were 0 – 30 (topsoil) cm and 30 – 60 cm (subsoil). VESS method was used to assess the topsoil structure quality, whereas SubVESS method was used to assess the subsoil structure quality. The collected data were subjected to analysis of variance (ANOVA), multivariate analysis of variance (MANOVA) and Person correlation coefficient analysis at a 95% confidence interval ($p \leq 0.05$) using IBM SPSS statistics 29.0 statistical software. A focussed literature review carried out in this study showed that there is little research on the adoption of VESS by the intended end users, which are the land managers and farmers. It also revealed a gap on the application and effectiveness of the VESS method to distinguish the impact of long-term no till systems on the soil structure quality.

The assessment of soil soil structure with the VESS method in long-term no-till systems revealed that: The VESS method is effective for assessing soil structural quality in routine soil characterisation. However, it must be noted that most soil structure attributes tend to be soil and site specific. The VESS and subsoil visual evaluation of soil structure (SubVESS) scores indicated poor structure for topsoil and subsoil in NT and conventional tillage (CT) at Tshivhilwi. At Dzingahe the topsoil structure quality was fair in NT and poor in CT while subsoil structure quality was moderately good in NT and poor in CT. The bulk density was relatively lower (1.20 – 1.57 g/cm^3) showing that the soils were not compacted. Organic carbon was between 1.50 and 2.00% except at Dzingahe in the 0 – 30 cm soil depth where it was above 2.00%.

The assessment of pore characteristics, CO_2 efflux and unsaturated hydraulic conductivity of soils under long term no-tillage system showed that no-tillage had a higher total porosity and estimated pore connectivity than CT quantified with X-ray computed tomography, although at Dzingahe total porosity in the topsoil was about 1% higher in CT. The volume of micropores increased with depth. Cracks larger than 5 mm constituted highest percentage of the total pore volume due to the high percentage of active clay. Conventional tillage had almost three times higher unsaturated hydraulic conductivity than NT at Tshivhilwi. Carbon dioxide efflux increased with soil moisture content and it was more in during the wet and dry season.

The effect of no-till duration on soil aggregate size distribution, stability and aggregate associated carbon revealed that macro-aggregates (0.212 – 2 mm) constituted the largest proportion of aggregates with percentage contribution of > 60% in the short-term and long-term no-tillage system. Mean weight diameter (MWD) was greater in

NT and CT in the short term and long-term no-till respectively. Subsoil indicated a more stable structural stability than topsoil. However, when comparing NT only in the two periods MWD was greater in the short term. All aggregate fractions contained more organic carbon in the topsoil but micro-aggregates had higher organic carbon than all of them in both short-term and long-term no-till systems. In conclusion, although there were some inconsistencies between the tillage systems, duration and soil depths, overall NT showed better results than CT. No-tillage has a potential to sustain good soil structure and related parameters. Frequent monitoring of soil structure induced by NT is required to detect any changes that may lead to degradation, and this can be achieved by using VESS as the monitoring tool.

Key words: Tillage, soil structure, soil depth, soil quality, VESS, SubVESS

CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

Soil structure, as described by Ball *et al.* (2007) is a complex soil property, partly related to inherent characteristics of particle size and clay mineralogy and also anthropogenic influences related to land use and management. According to Filho and Tessier (2009), tillage management systems influence several soil properties such as reduced pore volume and size due to compaction, which on the other hand may affect the soil-water and air relation. Jabro *et al.* (2016) noted that tillage results in loosening, disturbance and manipulation of the soil. Furthermore, soil texture is among soil properties that determine the extent of soil loosening and overturning during tillage. Oliveira *et al.* (2020) indicated that long-term conventional, minimum, and no-tillage practices affect soil physical properties such as bulk density and aggregate stability, among others, and soil organic carbon content. Furthermore, this affect the overall structure of the soils under these tillage systems. The degree of the effect may vary among different soil textures and the management of the tillage systems over a period of time. Hence, the study was conducted in soils with high clay content in Thohoyandou. Generally, the soils in the study area are regarded as fertile, however, their structure is more likely to be compromised due to tillage management. No-tillage and/or conventional tillage cause changes in soil structure and related properties overtime which usually depend on how they are managed, although the focus was on no-tillage. Therefore, there is need for simple and cheap method(s) to monitor the development of soil structure as it is easily manipulated. Soil structure is related to several beneficial soil functions, for example, water storage and transportation, carbon storage and physical stability and support (Rabot *et al.*, 2018). Bronick and Lal (2005) also indicated soil structure influences soil water movement and retention, nutrient recycling, erosion, root penetration and crusting. Furthermore, it influences runoff, surface- and ground-water pollution and CO_2 emissions. Soil structural characteristics such as reduced pore geometry and continuity make soils more susceptible to crusting, compaction, reduced water infiltration, increased surface runoff, wind and water erosion and desertification (Lal, 2015).

Soil structure is regarded as one of the key soil quality indicators, thus, its evaluation and monitoring should be emphasized in soil management and conservation. There are a number of visual soil structure evaluation methods which are used as opposed to and/ concurrently with the traditional laboratory methods. These methods are carried out in the field where soil attributes related to structure are evaluated and rated based on the visual observations. The development of methodologies to characterise and determine management practices that control soil degradation and soil quality enhancement are highly recognised and receiving international interest (Zornoza *et al.*, 2015). According to Bünemann *et al.* (2018), soil quality is generally based on the approaches that focuses on the inherent soil properties or human management effects. Physical, chemical and biological properties can be measured to make conclusions on the soil quality (de Paul Obade and Lal, 2016a). Bünemann *et al.* (2018) reported that establishing sensitive soil attributes that reflect the capacity of a soil to function and can be used as indicators is an essential component of soil quality assessment. Doran and Zeiss (2000) and Karlen *et al.* (2003) highlighted that soil quality can be assessed based on inherent and dynamic soil properties such as texture and structure respectively and processes. Soil quality is strongly linked to soil structure, because poor quality soil structure may lead to problems such as susceptibility to compaction, erosion and desertification (Pagliai *et al.*, 2004).

Mueller *et al.* (2013) showed that visual soil structure quality methods for soil quality assessment such as visual evaluation of soil structure (VESS) are effective for controlling and monitoring the soil functions for sustainable agriculture. VESS is one of the field evaluation methods which are used to rate soil structure quality based on related parameters such as size and appearance of aggregates, visible porosity, and roots (Ball *et al.*, 2007 and Guimarães *et al.*, 2011). According to Guimarães *et al.* (2013) and Tuchtenhagen *et al.* (2018) the method is straightforward, time-saving and cost effective. Furthermore, Giarola *et al.* (2010) and Johannes *et al.* (2017) highlighted that the method is based on field measurements which means it provides instant interpretable results and does not require any sophisticated equipment. The VESS method was designed to assess the topsoil (~30 cm). The subsoil (~ 30 to 140 cm) is assessed by the Sub-VESS method which was developed from the VESS (Ball *et al.*, 2015; Emmet-Booth *et al.*, 2016). In contrast, porosity measurements are considered to quantify changes in soil structure instead of the traditional methods such as hydraulic conductivity and aggregate stability (Pagliai *et al.*, 2004). The quantification can be done by using techniques such as X-ray computed tomography (microCT) which is able to give a clear indication of the effects of tillage systems on soil pore space distribution and structure (Pagliai *et al.*, 2004; Pires *et al.*, 2017). This is a non-destructive procedure which requires specialized expensive equipment but it gives accurate characterization of soil parameters such as porosity at a microscale level. VESS can be used as alternative to enable farmers to do routine soil assessment and identify problems at early stages so as to guide management decision making.

Aggregation occur due to the rearrangement, flocculation and cementation of primary soil particles (Mohanty *et al.*, 2012). Furthermore, it is facilitated by soil organic carbon, the content of clay, oxides and carbonates and ionic bridging. However, some of the compounds in the soil are not involved in aggregation. According to Sekaran *et al.* (2021) soil aggregation, organic carbon and porosity are enhanced under long-term no-tillage than conventional tillage. But, the same soil properties are not always significant between these tillage systems under short term. Du *et al.* (2013) reported that soil macro-aggregate proportion was increased under no-tillage due to higher organic carbon and reduced soil disturbance compared to conventional tillage with mouldboard plough. The carbon stored in the aggregates is physically protected by them and its degradation is delayed (Das *et al.*, 2014). Six *et al.* (2000) indicated that soil organic matter is expected to be the main cementing agent in soils dominated with 2:1 clay minerals although it is not the only cementing agent in those dominated with oxide and 1:1 clay minerals. Mikha and Rice (2004) concluded that conventional tillage resulted in soil organic matter loss due increased aggregate disruption.

Soil pore characteristics such as size distribution, volume, connectivity and total porosity are strongly linked with soil structure, texture and compaction (i.e. bulk density). Soil bulk density and porosity are naturally connected and they have inverse relationship (Wardak *et al.*, 2022). In addition, bulk density and porosity are associated with soil compaction (Fu *et al.*, 2019). The impact of compaction on soil physical properties is through increased bulk density and strength, reduced total porosity and smaller pore size distribution (Gregory *et al.*, 2006). Generally, soils under no-tillage have higher bulk density and total porosity in the plough layer than under conventional tillage (Lipiec *et al.*, 2006). Although, the differences may extend to the lower soil depths in either tillage system. The Pore size distribution and network or connectivity controls the soil hydraulic properties and transport of gases and solutes (Munkholm *et* *al.*, 2012; Panday and Nkongolo, 2021; Pessoa *et al.*, 2022; Vogel and Roth, 2001). Tarquis *et al.* (2009) supported this by indicating that the spatial arrangement of primary soil particles and aggregates results to a complex pore space geometry that influence fluids and solutes transport. Yang *et al.* (2018) showed that soil pore characteristics affect soil water preservation and transmission. Hydraulic conductivity depends soil texture, bulk density, pore size distribution and drainable porosity (Macedo *et al.*, 2017). Water moves rapidly through macropores than micropores, therefore, sandy soils generally have higher infiltration rate than clayey soils. However, some clay soils are aggregated while others develop cracks when they are dry depending on the type and amount of clay minerals leading to high infiltration rates (Haghnazari *et al.*, 2015).

The loss of carbon from the soil in the form of CO_2 under different tillage systems is a challenge as it contributes to global warming. According to Riveros-Iregui *et al.* (2008 "soil CO_2 efflux is a natural process by which soil carbon is released into the atmosphere through autotrophic and heterotrophic respiration". Soil CO_2 is a product of the microbial decomposition organic matter (including crop residues) and plant respiration (Gong *et al.*, 2021). Tillage manipulate the soil which could lead to rapid release of this greenhouse gas to the atmosphere. The degree of manipulation can depend on the inherent soil properties such as texture more especially clay content. Sang *et al.* (2022) highlighted that clayey soils compared to sandy and loamy soils release more CO_2 when exposed to drying and wetting cycles. Wang *et al.* (2015) added that there is little that is known on the impact of multiple drying and wetting cycles caused by the frequency of precipitation on soil CO_2 emission. Furthermore; soil microbial activity, composition and population can be affected by the changes in soil water content during the wet and dry periods. Thus, there could be a difference in soil CO_2 emissions between the wet and dry season.

1.2. Problem statement

Intensive and continuous tillage practices cause soil degradation and, consequently, poor soil quality (Lal, 2015). The decline in soil structure quality is a global problem across cultivated agricultural lands, with South Africa being no exception. This decline is generally due to the response of some soils to management practices (such as tillage) and land uses (Six *et al*., 2000). Given the role that soil structure plays in the functioning of the soil, its declining quality may lead to degradation (Fernandez-Ugalde *et al.*, 2009). On the other hand, tillage system may to some degree, contribute to the disruption of soil structure, leading to the deterioration of other soil properties (e.g. pore size and network, total porosity, bulk density, soil organic carbon and aggregate stability) and water and air transmission (Sekaran *et al*., 2021). Gong *et al.* (2021) indicated that tillage effects on soil CO_2 emission are inconsistent and not well clarified. While management practices such no-till and fallowing are recommended to maintain, recover, and improve soil structure (Fernandes *et al.*, 2023; Fernández-Ugalde *et al.*, 2009; Liu *et al.*, 2021; Sekaran *et al.*, 2021), the impacts of the duration of such practices are still not yet well elucidated especially on clayey soils. Studies such as that of Soropa *et al.* (2022) and Montfort *et al.* (2021) have shown that it can take up to two decades of fallowing for organic carbon and the fertility of the soil to return to its original status. Information on the impact of no-till duration on the accumulation of carbon and aggregate size distribution is also still limited.

Soil structure is commonly assessed using qualitative methods such as characterizing it on the basis of class, grade and type (Díaz-Zorita *et al*., 2002), which lacks details on the state of its quality. There are developed semi-quantitative visual methods that have the potential to provide a more detailed assessment. Thus, VESS and SubVESS were selected. According to Emmet-Booth *et al*. (2016), moisture content interaction with the visual soil evaluation methods have received little attention. Pulido-Moncada *et al*. (2017) indicated that texture can be a limitation and affect the use of the VESS in different soils. The inclusion of crusting (which can be due to particle dispersion or slaking) in the scoring of VESS method can help to explain the infiltration rate (Guimarães *et al.*, 2017). These methods need to be explored to further integrate qualitative and quantitative data that will enable a comprehensive soil structure quality rating criterion because they have proven to be effective in detecting soil structure changes (Mutuku *et al*., 2021). Tillage has a significant impact on soil structure and related parameters over time compromising the overall soil quality and this tend to be site specific and hence the need to conduct this study. It is critical to assess and compare the effects of no-tillage and conventional tillage systems duration (long-term and short-term) on these parameters in different soil depths and environmental settings.

1.3. Rationale

Soil structure is one of the principal soil quality indicators, thus it is important to understand its dynamics. On the other hand, its quality is highly influenced by tillage and soil texture more especially clay content (Fernandes *et al.*, 2023; Topa *et al.*, 2021). Hence, the study investigated to what extent no-tillage duration affects the soil structure quality. Tillage has a direct effect on the transformation of soil structure (Liu *et al.*, 2021; Pires *et al.*, 2017). Generally, it is known that conventional tillage damages soil structure contrary to no-tillage which improves it (Khalid *et al.*, 2019; Liu *et al.*, 2021; Mondal and Chakraborty, 2022; Weidhuner *et al.*, 2021). The monitoring of soil structure quality is requisite for sustainable soil management. Soil properties such as texture, amount and type of clay minerals, organic matter content, microbial activity, salinity and sodium adsorption ratio determine the nature of soil structure (Bronick and Lal, 2005; Leuther *et al.*, 2023). The water and air movement is highly affected by the strength and stability of the soil aggregates hence it is also critical to evaluate how they are impacted by soil tillage. There is a growing use of visual soil structure quality evaluation approach. However, the approach still needs assessment in different soil conditions and tillage systems. However, based on the existing literature the use of such approaches are still uncommon in South Africa. Emmet-Booth *et al.* (2016) showed that VESS, SubVESS, Visual Soil Assessment (VSA), Le Profil Cultural and SOILpak are the widely used soil structure visual assessment methods. This study was focused on VESS and SubVESS methods as they are more rapid, direct and provide readily interpretable results, which makes them easy to implement and replicate. Furthermore, the two methods complement each other and have the potential to be improved. The visually assessed soil structure quality attributes, together with related quantitative field and laboratory-measured parameters enable for an in-depth understanding of their role in soil structure quality. Thus, contributing to the execution of sustainable soil management practices that will maintain a good soil quality.

1.4. Aim and objectives

1.4.1. Aim

The aim of the study was to visually assess the structure dynamics of the soils with relatively high clay content and profiling related structural parameters, under long term no-tillage systems in a subtropical climate.

1.4.2. Objectives

The objectives were to:

i) Review existing literature on the use of VESS method to assess soil quality.

ii) Determine the effect of long-term no-tillage system on structure dynamics of clayey soils.

iii) Assess the effect of long-term no-tillage on pore characteristics, CO_2 efflux and unsaturated hydraulic conductivity of clayey soils.

iv) Assess the impact of tillage duration on soil aggregate size distribution, stability and aggregate associated carbon.

1.5. Hypotheses

i) Visual evaluation of soil structure (VESS) cannot be used to assess soil quality.

ii) Long-term no-tillage systems do not have an effect on structure dynamics of clayey soils.

iii) Long-term no-tillage does not have any effect on pore characteristics, CO_2 efflux and unsaturated hydraulic conductivity.

iv) Tillage duration does not have any impact on soil aggregate size distribution, stability and aggregate associated carbon.

CHAPTER 2

LITERATURE REVIEW

2.1. Soil quality indicators

The soil quality concept has been an evolving process through its definition and the identification of properties that can be used in the holistic assessment of soils and relating them to soil processes and management practices (Seifu and Elias, 2018). The concept of soil quality was developed with two different areas of emphasis (education and assessment) which are based on soil science principles (Karlen *et al.*, 2003). Soil quality can be assessed based on inherent and dynamic soil properties and processes (Doran and Zeiss, 2000; Karlen *et al.*, 2003). The authors further explained that the inherent properties are generally assessed on the entire soil profile while the dynamic properties are assessed only top soil. The dynamic properties such as soil structure, are easily affected by land use and management practices. On the other hand, the opposite occurs with the inherent physical and chemical properties. Oliver *et al.* (2013) also indicated that there are two types of soil properties: intrinsic and dynamic. Inherent soil properties, such as soil texture or clay type, are valuable for initial soil characterization but not for tracking change over time because they alter little to nothing with land use and management practices. However, dynamic soil properties, such as pH and carbon content, do alter in response to management practices. The U.S. National Cooperative Soil Survey started a standard program to assess and catalogue disturbance-sensitive dynamic soil properties for all lands in the U.S. in response to increased demand for information on soil quality and function (West *et al.*, 2010). The inventory of the dynamic soil properties aims to comprehend the effects of land use and management on them and soil function for U.S. soils. Moreover, providing tools for land managers and users to better plan and implement management strategies to preserve and improve soil quality and ecosystem services. This kind of initiative can be expanded to other countries or even to a global scale in order to combat soil degradation by establishing accessible standard procedures to evaluate the dynamic soil properties as affected by land use and management in specific soils and locations.

Indicators of soil quality are properties that are able to provide the soil's capacity to perform critical environmental functions (Zornoza *et al.*, 2015). Some of the key soil quality indicators and their importance are presented in Table 2.1. Soil quality conclusions can be made by measuring the physical, chemical and biological properties (Dexter, 2004; de Paul Obade and Lal, 2016b). There is an interaction between these soil properties, hence, in some cases it is difficult to make conclusions on soil quality by measuring only one parameter. Biological, physical and chemical indicators depend on each as determinants of soil quality (Reeves, 1997). Furthermore, as challenging as it is to create a standard for each of these indicators that is universally acceptable, it is even more challenging to integrate these parameters into a working whole, applicable in variety of soils and agroecosystems. Muñoz-Rojas *et al.* (2018) reported

Table 2.1. Key soil indicators for soil quality assessment and their rationale for selection (Seifu and Elias, 2018)

Selected indicator	**Rationale for selection**
Organic matter	Defines soil fertility and soil structure, pesticide and water retention
Topsoil-depth	Estimate rooting volume for crop production and erosion
Aggregation	Soil structure, erosion resistance, crop emergence an early indicator of soil management effect
Texture	Retention and transport of water and chemicals
Bulk density	Plant root penetration, porosity, adjust analysis to volumetric basis
Infiltration	Runoff, leaching and erosion potential
pH	Nutrient availability, pesticide absorption and mobility
EC	Defines crop growth, soil structure, water infiltration
Pollutants	Plant quality, and human and animal health
Soil respiration	Biological activity, process modelling, estimate of biomass activity, early warning of management effect on organic matter
Forms of nitrogen	Availability of crops, leaching potential, mineralization/ immobilization rates
Extractable N, P and K	Capacity to support plant growth, environmental quality indicator

EC = electrical conductivity, N = nitrogen, P = phosphorous, K = potassium that despite the significant potential advantages of employing soil quality indicators as tools in ecosystem restoration efforts, the calibration and creation of global parameters continue to be difficult due to the wide range of soils, ecosystems and climates. Measuring soil physical, chemical, and biological quality indicators can provide insight into a soil's ability to function (Shukla *et al.*, 2006).

The influence of organic matter, or more particularly soil carbon, on soil quality is the most well-known and transcends all three indicator groups (United States Department of Agriculture, 2008). To track changes and identify trends in soil quality deterioration or improvement for different ecosystems, it is necessary to select key indicators and their threshold values that must be maintained for appropriate soil functioning (Arshad and Martin, 2002). It is acknowledged by many studies that soil organic matter is an effective soil quality indicator due its impact on soil productivity and quality (Barut and Celik, 2017). According to Zornoza *et al.* (2015) soil organic carbon is the most used indicator for soil quality assessments before pH, electrical conductivity and nutrients (as indicators for soil fertility). While, the most commonly used physical indicators include aggregate stability, bulk density and particle size. Thus, maintaining soil organic matter is essential for sustaining soil quality (Reeves, 1997). A range of soil physical properties, including moisture retention curve, bulk volume, mechanical stress resistance of the soil and fluid transfer characteristics are correlated with soil organic matter content (Johannes, Matter, *et al.*, 2017).

Understanding the characteristics of soil quality and how they relate to sustainable agriculture is crucial for identifying related issues and determining the best course of action for resolving them (Seifu and Elias, 2018). Soil quality is centred on the physical, chemical and biological qualities which are dependent on each other. Soil physical quality is clear in different ways e.g. poor quality soils may exhibit symptoms such as surface runoff, poor water infiltration, hard-setting, poor aeration, poor workability and poor rootability (Dexter, 2004). The opposite occurs in a soil with good physical quality. In addition to regulating soil physical condition, soil physical quality also influences the biological and chemical conditions of the soil (Koureh *et al.*, 2020). All of the ecosystem services that soils provide, such as the production of food, fiber, feed, and fuel, soil erosion control, air and water quality improvement, soil C dynamics and sequestration, nutrient cycling, and biodiversity, among others, are impacted by changes in the physical properties of the soil (Blanco-Canqui and Ruis, 2018). Aggregate size distribution and stability, water retention, compaction and porosity are commonly referred to as "dynamic physical quality indicators" and have been broadly utilized as indicators of soil quality to assess the impacts of management on soil physical quality (Fernández-Ugalde *et al.*, 2009). Soil physical quality indicators give information related to aeration and hydrologic state of the soil, such as water entry into soil and soil's ability to retain water within the root zone (United States Department of Agriculture, 2008). Furthermore, the soil physical properties reveal details related to the soil's capacity to endure physical pressures related to splashing raindrops or rapid inflow of water into the soil which can cause aggregate disintegration, dispersion and erosion.

2.2. Effect of management practices on soil quality

The impact of different agricultural management practices on soil quality has come to light more and more over the years, and this has sparked an increased interest in measuring the consequences of these practices in order to control restrictions and assure their sustainability (Oliver *et al.*, 2013). One objective of soil quality research is to learn how to manage soil in a way that improves its functions because soils respond to management differently depending on the inherent properties and landscape (Seifu and Elias, 2018). Furthermore, the management decisions on soil affect properties such as soil structure, soil depth, soil organic matter, and water and nutrient holding capacity. The development of agricultural management practices that match the requirements for the production of food and fiber with those for the maintenance of the environment is a challenge (Doran and Zeiss, 2000). However, the development of methodologies to describe and define management strategies that influence degradation and improve soil quality is becoming more widely recognized and pursued internationally (Zornoza *et al.*, 2015). To assess changes in soil quality brought on by various management practices, a minimum data set (MDS), must be measured (Arshad and Martin, 2002). The diversification of tillage management under different moisture content may create new conditions for soil structure dynamics (Roger-Estrade *et al.*, 2009). Thus, leading to modification of several soil physical, chemical and biological properties over time, therefore soil quality. No- and zero-tillage practices are potential alternatives to conventional tillage for production that improve soil physical properties, infiltration and preserve soil moisture storage (Jabro *et al.*, 2016).

Thus, more research is required to assess the impact of different tillage systems on hydraulic and physical characteristics of clayey soils.

2.2.1. Conventional agriculture and soil quality

Frequent use of heavy agricultural implements in conventional agriculture increases the vulnerability of the soil to erosion and damages the natural soil structure (Kazimierczak *et al.*, 2016). Although deep tillage on wet or saturated soils has the potential to harm the soil, it was an effective method in conventional agriculture for restoring damaged soil structure (Roger-Estrade *et al.*, 2009). Some conventional agricultural systems have a substantial impact on soil structure in that it tends to be weak, which results in increased bulk density and compaction (Arriaga *et al.*, 2017).

Pagliai *et al.* (2004) conducted a study where the findings supported that conventional ploughing cause more significant modifications to the physical characteristics of the soil, which in turn damaged the soil structure. Conventional tillage system invert soil during land preparation to loosen the topsoil, incorporate crop residues and control weeds (Crittenden *et al.*, 2015). Ball *et al.* (2005) showed that soil structural formation can be influenced by the physical incorporation of organic matter. The erosion and loss of organic matter in soils caused by conventional tillage practices may have a negative impact on long-term soil productivity (Mathew *et al.*, 2012). Changes in soil compactness have an impact on the hydraulic, thermal and aeration characteristics of soils that control mass and energy flow and therefore root growth and crop production, particularly at high levels of agricultural mechanization (Özgöz, 2009).

2.2.2. Conservation agriculture and soil quality

According to Palm *et al.* (2014) conservation agriculture “is a system of agronomic practices that include reduced tillage or no-till, permanent organic soil cover by retaining crop residues, and crop rotations, including cover crops”. Conservation agriculture promotes least soil disturbance through zero tillage, balanced chemical inputs application required for soil quality improvement and adequate residue and waste management (Dumanski *et al.,* 2006). It also promotes most soils to have greater levels of natural physical weather protection (dry or wet periods, raindrops, wind), good structure and cohesion, and extensive bioactivity and biodiversity (Bhan and Behera, 2014). Figure 2.1 shows that Africa has the lower area under conservation agriculture. This could also highlight that the adoption of conservation agriculture which incorporate no-tillage in South Africa is low despite its reported benefits. In order to improve some soil quality features in a high clay soil found in semi-arid climate regions, conservation tillage strategies including no-tillage and reduced tillage may be preferable to conventional tillage (Barut and Celik, 2017). Conservation agriculture acknowledges the significance of the topsoil (~ 0 - 20 cm) as the most active region of the profile which is prone to degradation (Dumanski *et al.,* 2006). There is inconsistency in the reported effects of conservation agriculture on soil water transmission and retention, field capacity, saturated hydraulic conductivity, permanent wilting point, plant available water capacity and pore size distribution (Eze *et al.*, 2020). As a result, these soil hydraulic properties have received little research recognition.

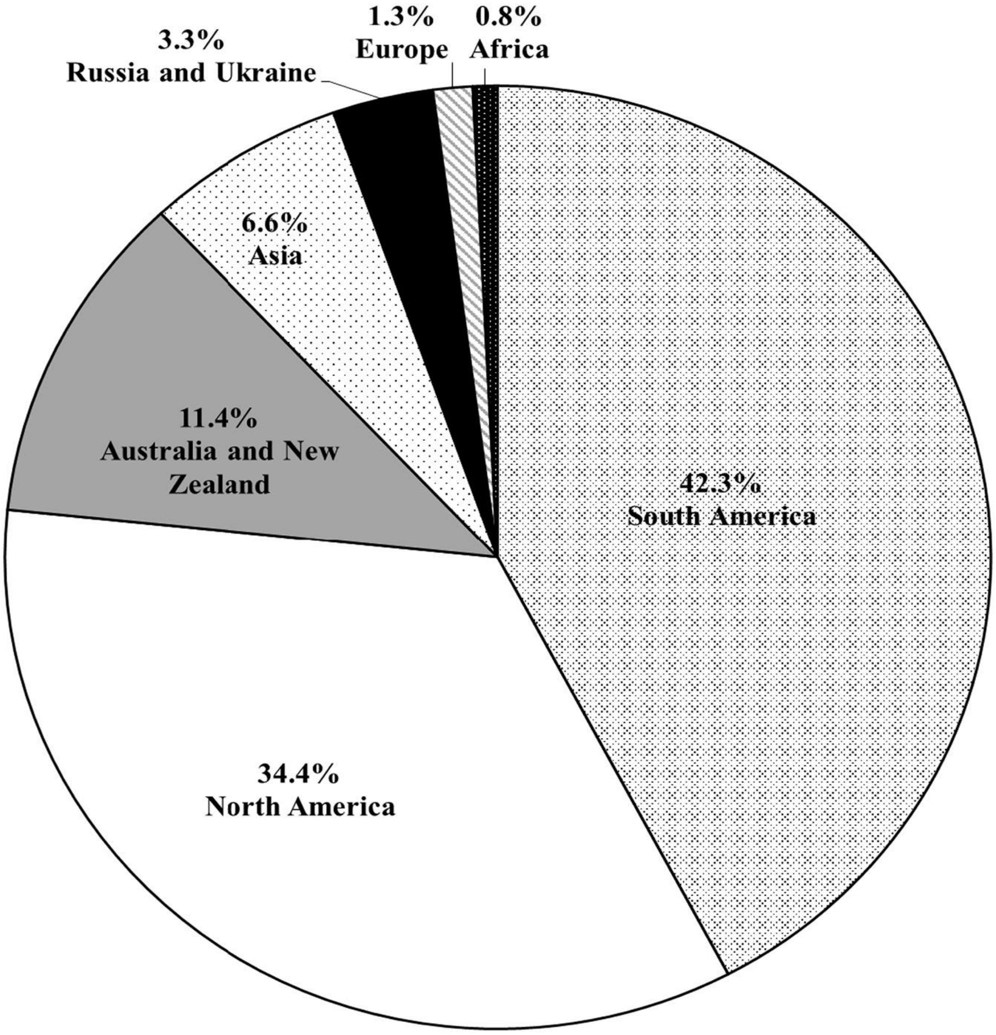


Figure 2.1: Percentage of area under conservation agriculture by continent or major land area (Panday and Nkongolo, 2021)

Panday and Nkongolo (2021) indicated that no tillage, crop rotation and cover crop have positive impact on soil pore space indices. Continuous no-tillage of more than seven years has significantly influenced the improvement of water stability, aggregate distribution and water retention properties (Fernández-Ugalde *et al.*, 2009). Furthermore, the improvement of soil structural properties such as aggregate stability and pore-size distribution have increased plant-available water content under No-tillage. This type of tillage system can help improve the soil properties and productivity of degraded agricultural lands all over the world (Blanco-Canqui and Ruis, 2018). Improved soil aggregation is frequently linked to management practices that increase soil organic matter (Arriaga *et al.*, 2017). However, even soil with sufficient organic matter may have undesirable physical characteristics or have undergone significant degradation where the physical properties are below optimal.

2.3. Interaction between soil structure and other properties

Soil structure is related to several beneficial soil functions, for example, water storage and transportation, carbon storage and physical stability and support (Rabot *et al.*, 2018). Bulk density and penetrometer resistance are important soil structural parameters that measures of soil compaction (Barut and Celik, 2017). Various problems and restrictions at farm level are brought on by the deterioration of soil structure, including restrictions on infiltration, water storage, and soil aeration, increased erosion, and decreased soil fertility and crop development (Fell *et al.*, 2018). Both semi-permanent qualities (e.g. mineralogy) and ephemeral properties (e.g. aggregate and pore size distribution) of soil structure are subject to variation with climate, soil moisture, season and agricultural activities (Topp *et al.*, 1997). Soil aggregate formation is essentially dependent on the organic matter supply, although it is also strongly impacted by the type of soil mineralogy (Ball *et al.*, 2005). In addition, microorganisms play a key role in soil structure formation, but they are also influenced by the type of structure that is created.

Aggregation is crucial for allowing water infiltration, minimizing soil erosion, providing enough habitat space for microorganisms and ensuring that roots and microorganisms receive enough oxygen (Franzluebbers, 2002). Understanding how a soil aggregate stores and interacts with soil organic carbon is crucial for creating management strategies to improve carbon sequestration at regional and global scales since aggregation is the core of all mechanisms of carbon sequestration (Kumar *et al.*, 2013). The protection of soil carbon and nutrients and soil erosion severity at macro- and micro-scale level can be influenced by the changes in soil aggregate stability

(Blanco-Canqui and Ruis, 2018). Soil organic carbon is the primary component of soil organic matter which might be used as a proxy for soil structural stability (Jensen *et al.*, 2019). This soil structural stability is the capacity of soil structure to withstand water and/or mechanical stresses.

Soil properties such as bulk density, penetration resistance, micro- and macro-porosity, and infiltration rate are helpful because they reveal how soil structure functions to air, water and support for the plants (Guimarães *et al.*, 2017). Generally, soils with low bulk density, high porosity, fast water movement under saturated and unsaturated situations and effective infiltration and drainage have high organic matter content (Arriaga *et al.*, 2017). Reduced pore geometry and continuity are soil structural characteristics that are typically affected by soil physical degradation (Lal, 2015). This makes soils more susceptible to crusting, compaction, reduced water infiltration, increased surface runoff, wind and water erosion, desertification and increased soil temperature fluctuations.

2.4. Soil structure effect on water and air relations

Soil structure greatly influences the aeration and water content because of the distribution and network of the pores. The ideal situation is when there is a balance between the air-filled pores and water-filled pores. Soil water and gas are stored and transported through and/or in the pores (Arriaga *et al.*, 2017). Furthermore, as much as the total porosity is important, but pore size distribution is key to good soil quality. The soil water content affect the movement of air in the soil, for example when the water content is high the air-filled pores decreases (Sun *et al.*, 2022). This because the excess water will occupy the pores that are supposed to be filled with air, thereby reducing the air circulation. Soil gas concentrations and soil-atmosphere gas fluxes change overtime and vary significantly from ecosystems to soil gas profiles (Maier *et al.*, 2020).

2.4.1. Soil water movement

Water movement into the soil is important for recharging the aquifers, maintaining the base flow of rivers, availability of more water for vegetation cover maintenance and development (Pan *et al.*, 2018). In addition, water infiltration reduces soil erosion, increases plant available storage and groundwater recharge (Lipiec *et al.*, 2006). Aboukarima *et al.* (2018) reported that infiltration rate usually decreases with either an increase in sodium adsorption ration or decrease in salinity. This is because high salt concentration promote flocculation of soil particles whereas high sodium adsorption ratio promote cause dispersion, therefore, affecting soil structure and porosity. Infiltration occur when there is sufficient connected large pores in the soil (Haghnazari *et al.*, 2015). Drainage results from soil physical properties such as porosity, particle size distribution and morphology along the profile (Asgari *et al.*, 2018).

No-tillage has the potential to increase infiltration than conventional tillage (Blanco-Canqui and Ruis, 2018). Alletto *et al.* (2022) and Amami *et al.* (2021) reported an increase in infiltration capacity and stability under no-tillage than conventional tillage. Conventional tillage may temporarily increase macropores which normally collapse when the soil settles and further destroys the earthworm or insect burrow network to fewer connected pores that limits infiltration (Thierfelder *et al.*, 2013). Pareja-Sánchez *et al.* (2017) discovered an increased resilience to crust formation and soil degradation in 20 years of no-tillage which doubled water infiltration than in conventional tillage. During draught, soils with higher infiltration rate can maintain greater humidity (Kovář *et al.*, 2017). Furthermore, the rate of infiltration into soil affects the plant water supply.

2.4.2. Carbon dioxide (CO_2) diffusion from the soil

The movement of air in the soil occurs mainly through diffusion (Panday and Nkongolo, 2021). Soil air diffusion is more rapid in the macro pores than in the micro pores. Despite being a net sink for carbon due to plant growth and carbon fixation as refractory soil organic matter, soil often acts as a source of carbon dioxide (Maier *et al.*, 2020). Emission of soil CO_2 in agricultural fields is important and needs to be addressed quantitatively (La Scala *et al.*, 2006). Furthermore, no-tillage and conventional tillage affect the short term CO_2 emissions differently and significantly. Hao *et al.* (2023) reported that CO_2 flux in the deep soil layers are more sensitive to temperature than in the close to surface layers, therefore, CO_2 emissions in the deep layers will be extreme after exposed to higher temperature. Small changes in the stability between underground carbon storage and release could have major influences on CO_2 emissions (Nan *et al.*, 2016).

Chambers are used to measure accumulation of CO_2 diffusion from the soil surface (Tang *et al.*, 2003). Thus, are unable to give information about soil profiles and individual contributions at some soil depths, which is crucial for comprehending soil carbon dynamics. However, this is important to check the amount of CO_2 that is emitted to the atmosphere from the soil. Riveros-Iregui *et al.* (2008) stated that if the study is focused on seasonality, it is important to capture seasonal dynamics and spatial variability of CO_2 efflux that are mainly caused by changes in soil moisture content than recording diel dynamics that are due to plant activity and soil temperature. Carbon dioxide emissions can increase due to high soil respiration that is greatly stimulated by global warming, consequently further raising the temperatures (Hao *et al.*, 2023). The link between soil CO_2 efflux and its driving factors such as tillage, soil temperature and water content have not been sufficiently documented (Gong *et al.*, 2021).

2.5. Soil structure assessment

Soil structure assessment is challenging due to soil's extreme heterogeneity and complexity. The methods of assessing soil structure modifications range from pragmatic and rapid field examinations to comprehensive and time-consuming laboratory analysis (da Luz *et al.*, 2022). In recent years, visual soil evaluation methods have proliferated as a tool for the comprehensive assessment of soil structure (Munkholm *et al.*, 2013). Pulido Moncada *et al.* (2014) added that several visual field assessment methods have been developed recently to give a direct description of soil structure, assisting farmers in making quick decisions to enhance the structural quality of the soil and ensuring the soil's ability for sustainable production. For the management and protection of soil, regulations are required. As a result, soil structure quality assessment that cannot be contested must be available (Johannes *et al.*, 2019).

2.5.1. Methods of visual soil structure quality assessment

Macro-morphological parameters of soil are used to inform visual assessment procedures of soil structure with regard to the features and function (Mueller *et al.*, 2013). According to Giarola *et al.* (2010) visual soil structural quality classification criteria is based on morphology, presence of roots inside and outside aggregates, rupture resistance, and number and size of visible pores. Which means it is more detailed contrary to the traditional methods such as aggregate stability, bulk density and soil organic carbon analysis. According to Guimarães *et al.* (2013 and Tuchtenhagen *et al.* (2018) the methods are straight forward, time-saving and cost effective. There is a need to expand the validation of simple visual assessments in order to encourage scientists and farmers to adopt easy but accurate indicators for assessing and monitoring soil structural quality and soil degradation (Pulido Moncada *et al.*, 2014). A visual assessment of the soil can be used to estimate the soil quality at the moment of measurement and with more frequent assessments, can quantify change (Ball *et al.*, 2017).

Guimarães *et al.* (2017) showed that the visual evaluation of soil structure (VESS), Sub-VESS, visual soil assessment (VSA), Profil Cultural and SOILpak are the commonly used soil structure quality evaluation methods. They are categorised into topsoil-focused spade methods and topsoil and subsoil focused profile methods. It is important to note that some of the methods are designed for specific soils which in some cases are found in specific parts of the world. But with more research these methods can be used in a variety of soils which eventually will be universal. Emmet-Booth *et al.* (2016) stated that the choice of the method depends on the operator's expertise, area, and objectives, but all the visual methods give information that cannot be obtained with the quantitative measurements. VESS is a practical and dependable method that incorporates physical functions (such as root growth water availability and aeration) related to soil structural and physical quality (Cherubin *et al.*, 2017). Generally, the visual evaluation methods showed their potential for both direct on-field assessments and laboratory observations by demonstrating their efficient sensitivity for identifying changes in soil structural quality, independent of soil texture (Lin *et al.*, 2022). Under conditions where spade methods can provide sufficient information for management and decision making, it would not be compulsory to assess the soil further into the lower depths with profile method(s) considering time, weather and budgetary constraints. The deployment of profile methods in addition to spade methods can be justified where the spade method(s) cannot capture all the required information for decision making (Emmet-Booth *et al.*, 2019).

CHAPTER 3

THE USE OF VISUAL EVALUATION OF SOIL STRUCTURE (VESS) METHOD TO ASSESS SOIL QUALITY: REVIEW

Abstract

Soil structure is a dynamic soil property that can be easily altered by anthropogenic and natural activities and thus can be used as indicator to identify and monitor changes in soil quality due to these activities. There are several soil structure visual assessment methods which are classified into two broad methods: the spade (for topsoil) and profile methods. One of the commonly used spade method is Visual Evaluation of Soil Structure (VESS) which is easy, fast and cheap. The VESS method was developed in 1959 but was called Peerlkamp test and modified over the years until it was given the current name. The VESS method can also be carried out together with subsoil Visual Evaluation of Soil Structure (SubVESS) when there is a need to assess the subsoil structure. This current study reviewed the application of several soil structure visual assessment methods to detect changes resulting from different management practices and land uses, with a special emphasis on the use and applicability of VESS. The main objective was to probe the existing literature on the capabilities and limitations of the VESS method to detect changes in soil structure quality. The literature between 2000 and 2022 used in this article was gathered from google scholar and science direct databases. VESS was found to be sensitive enough to detect changes in soil structural quality and therefore has a capacity for direct in-situ assessment. The review also showed that VESS is useful in early detection of top soil structure modification and hence immediate soil management decisions can be made. This can help reduce dependence on or complement quantitative field and laboratory assessments of soil structure status that require expensive and sophisticated instruments. We have noted that the subjectivity of the VESS method will remain a challenge in the broader community of land users especially for the beginners. The VESS method can be developed further by adding more assessment parameters such as soil fauna and recommendations based on specific land uses and management practices.

Key words: Soil structure, Visual Evaluation of Soil Structure, soil quality, soil physical properties

3.1. Introduction

Soil structure is a dynamic soil property, that it can be easily altered by anthropogenic and natural activities (Ghezzehei, 2012; Karlen *et al.*, 2003; Or *et al.*, 2021; Osman, 2013; West *et al.*, 2010). Wetting, drying, freezing, thawing, and raindrop impacts are some of the natural processes that can alter soil structure (Osman, 2013). Similarly, soil management practices that have an influence on soil structure include tillage, irrigation, fertilizer and manure application, liming and cropping patterns. Soil structure have semi-permanent attributes (mineralogy of primary particles) and temporary attributes (e.g., pore and aggregate size distribution) that change with season, climate, soil moisture content and agricultural activities (Topp *et al.*, 1997). Thus, it can be used as an indicator of physical soil quality (Muñoz-Rojas *et al.*, 2018). Differentiating between natural and managed soil structure is the first step towards demystifying it and advancing knowledgeable expectations concerning its role and management (Or *et al.*, 2021). The authors further defined natural and managed structure as follows: "natural soil structure is the cumulative ecological legacy and soil constituent architecture by natural aggregation and bioturbation that support soil functioning under given climatic conditions" and "managed soil structure by tillage is the breakup and arrangement of soil constituents to support uniform and favourable conditions for crop seeds and root zones to maximize yields". Traditionally, soil structure is qualitatively characterised based on the shapes of the aggregates into types, on size of the peds into classes, and on distinctness and stability of the aggregates into grades (Ghezzehei, 2012; Osman, 2013). Even though soil structure is generally classified qualitatively, the visual methods offer a semi-quantitative assessment which gives ore details on its quality. The visual soil structure assessment methods have been in existence for some years but not widely used globally, however, they have recently gained attention in research.

There are several soil structure visual assessment methods which are classified as spade and profile methods (Emmet-Booth *et al.*, 2016). As indicated by Emmet-Booth and co-authors the following are spade methods: spade diagnosis, Peerlkamp method, the Werner method, extended spade diagnosis, spade analysis, soil quality scoring procedure, Visual evaluation of soil structure, Thinksoils manual, the Diez method, Visual Soil Assessment and FAL method. Profile methods are: Le Profil Cultural, Whole Profile Assessment, SOILpak and Subsoil Visual Evaluation of Soil

Structure. Generally the spade methods are used to assess the soil structure quality in the topsoil depth (~ 30 cm), while the profile methods are used for the whole soil profile assessment of soil structure (~1 m). The methods vary in terms of execution and require some level of soil science expertise. However, visual evaluation of soil structure (VESS) is regarded as the most simple and straight forward method, thus, it is easy to use for non-experts. Decision-makers require scientific, simple and cheap methods to assess soil quality and function changes for proper management of agricultural soils (Bai *et al.*, 2018). This support the use of VESS to enable frequent assessment and/or monitoring of soil quality. The state of soil structure quality can be used as a direct measure of soil quality. Visual soil structure assessment is a technique that involves assessing selected key soil structure parameters to determine its quality. The VESS method was originally developed as Peerlkamp test to assess the anthropogenic effects on the structure quality of topsoil (Emmet-Booth *et al.*, 2016) and has evolved ever since its inception.

VESS is one of the soil structure assessment methods and has been gradually receiving recognition from researchers for several years in some parts of the world (Leopizzi *et al.*, 2018). Furthermore, it is the most commonly used visual top soil structure assessment method (Guimarães, Lamandé, *et al.*, 2017) because of its simplicity and rapidness. The VESS method was designed to assess about 0 - 30 cm of the topsoil. Subsoils are assessed by a method called the SubVESS where VESS is used. The SubVESS was developed from the VESS to assess soil from ~ 30 to 140 cm (Ball *et al.*, 2015; Emmet-Booth *et al.*, 2016). The depth of SubVESS is not constant where 30 cm is the upper limit and 140 cm is the lower limit (Ball *et al.*, 2015). The assessment is generally done in agricultural lands to identify and monitor changes in soil structure as a result of anthropogenic effects. The type of management system and land use have an impact on soil structure. VESS is important for providing a broad soil quality information as an initial test and could also be used as guide to soil sampling scales and type of samples required (Ball *et al.*, 2017). It was shown that the capacity and consistency of VESS have been tested by researchers around the world (Tuchtenhagen *et al.*, 2018). Thus, it is without a doubt that VESS can help in early detection of soil structure degradation and decision making regarding management. Thus, it can be used as a monitoring tool in soil structure recovery because of its feasibility. Furthermore, the use of VESS to assess and monitor soil structure reduces soil testing costs as it does not require chemicals and/or sophisticated instruments (Guimarães *et al.*, 2017).

VESS together with some other visual methods of soil structure can be complementary to the traditional laboratory methods and/or used as an alternative in soil quality assessment (Mutuku *et al.*, 2021). The sustainability and conservation of soil quality requires simple monitoring tools such as VESS to enable regular routine soil quality characterization that can give instant results in the field. VESS has the potential to detect the changes in soil structure quality in the topsoil, where if further assessment is required in the subsoil, SubVESS can be used. However, field and laboratory quantitative measurements in some cases may be necessary to validate the outcome of the visual assessment by putting numerical values on the key parameters of soil structure. With that said, this paper intend to promote the use of VESS in research and land and/or soil management. Researchers can use it as an in-situ tool to obtain immediate information about soil quality alternative to the traditional field and laboratory methods. Farmers and land managers can also use VESS instead of laboratory analyses thus reducing the costs for routine soil characterization. Moreover, they can do the assessment independently and monitor real time changes in soil structure. The objectives of this review are (i) to emphasize the potential of VESS method in routine soil characterization and (ii) to identify possible research gaps on the use of VESS method is soil quality assessment.

3.2. Literature gathering

The literature between 2000 and 2022 used in this article was gathered from google scholar and science direct databases. The following key terms were used in combination to search the relevant articles: visual evaluation of soil structure (VESS), visual soil structure assessment, soil structure, soil quality, soil physical properties, and quantitative methods of characterising soil structure. Since the focus was on the use of VESS, articles that involved VESS were considered over some others even if they were covering visual soil assessment methods. It is evident that there is more research on visual soil structure assessment methods that has been published recently. However, only those that were relevant to the topic were considered and synthesised in this review. Each of the used articles was reviewed in relation to the use of VESS method to assess soil quality and its applicability in soil research.

3.3. Soil structure as an indicator of soil quality

Soil structure is defined as "the spatial arrangement and binding of soil constituents and the legacy of biological agents that support physical, chemical and biological functions in soils" (Or *et al.*, 2021). It is regarded as a universal soil quality indicator (Ball *et al.*, 2017). Soil structure is a principal parameter that is dependent on and/or affects several physical, chemical and biological properties (Bronick and Lal, 2005). Soil quality is strongly related to soil structure, thus, soil structure degradation may cause environmental damage like erosion, desertification and compaction susceptibility in intensive arable lands (Pagliai *et al.*, 2004). Soil parameters that are sensitive to management practices like structure are appropriate as indicators of soil quality (Arshad and Martin, 2002). Pore-size distribution and dry and wet soil aggregate stability are among the sensitive measures of soil structural quality (Blanco-Canqui and Ruis, 2018; Pagliai *et al.*, 2004). A good soil structure and aggregate stability are beneficial for improving soil fertility, agronomic productivity, porosity and erosion resistance (Bronick and Lal, 2005). Generally, soils with good structure have stable aggregates while those with poor structure have single grained, massive and compacted structures (Ghezzehei, 2012; Osman, 2013). An aggregated soil structure is made up of secondary particles with porous clusters of primary particles held by different organic and inorganic binding agents (Topp *et al.*, 1997). Soil aggregate formation is promoted by SOM, microbial activities and polyvalent cations on colloidal surfaces (Osman, 2013).

Soil quality indicators vary among land uses, climates and soils (Lal, 2015) and they reflect the soil's capacity to function (Shukla *et al.*, 2006). Soil quality has three key components: physical, chemical, and biological quality (Dexter, 2004), and each comprises a list of important indicators (Lal, 2015) which interact. The soil physical quality indicators are: aggregate stability and amount, aeration, porosity, water transmission and retention, effective root depth, soil temperature regime and heat capacity. Chemical quality indicators: cation exchange capacity, pH, nutrient availability and favourable elemental balance (no toxicity or deficiency). Biological quality indicators include: soil fauna and flora, absence of pathogens and pests and microbial biomass C. Soil pH, aggregate stability, water-holding capacity, organic matter and number of earthworms can be used as indicators to assess the effect of management practices on soil quality (Bai *et al.*, 2018).

3.4. Development of the VESS method

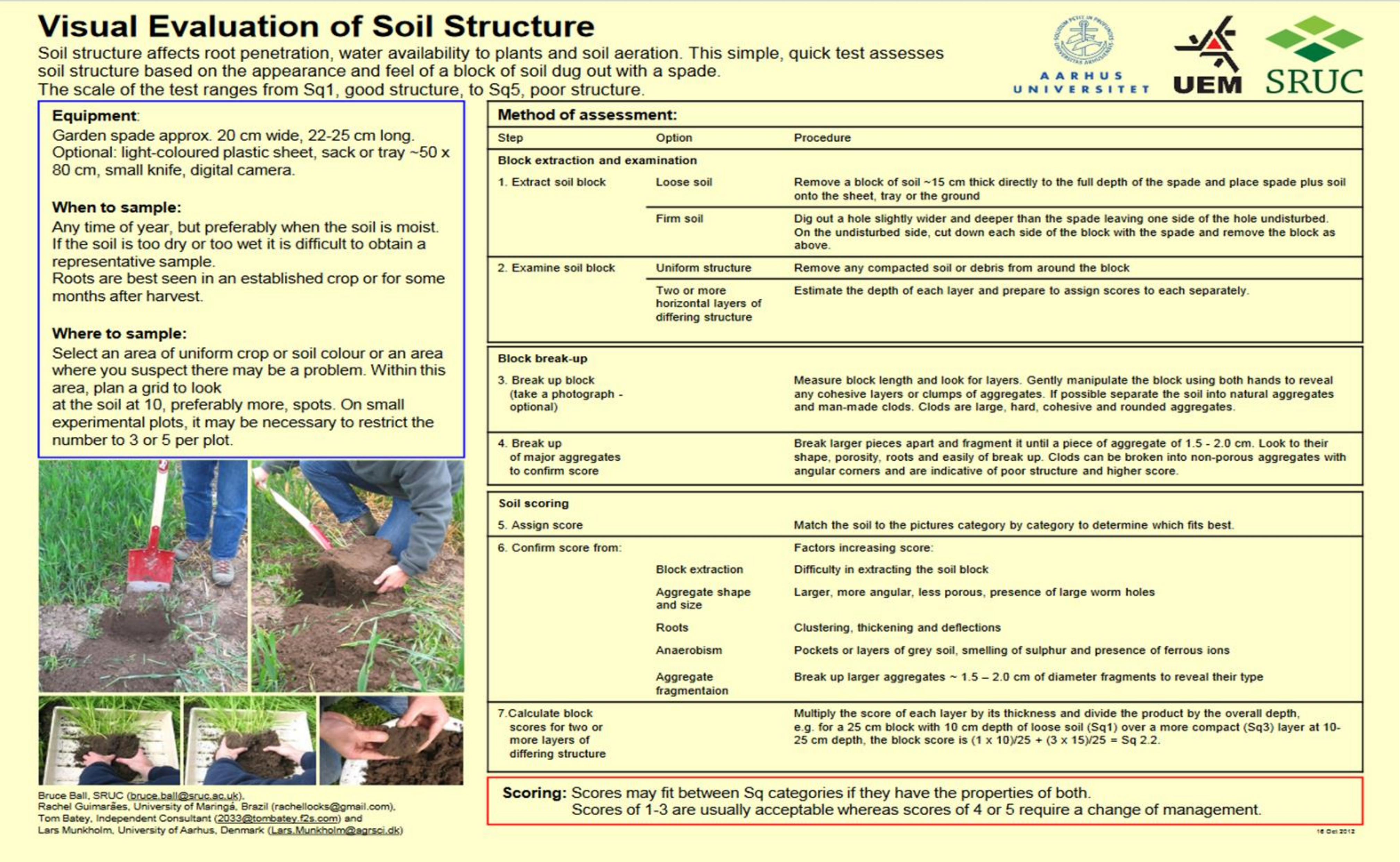
The Peerlkamp test (Peerlkamp, 1959) is one of the first visual soil structure assessment methods that was developed. This method was a modification of the method that was tested by Ferwerda in 1946. The author was aiming to develop a simple semi-quantitative soil visual evaluation method that is time-efficient and repeatable. It was regarded as subjective (Mueller *et al.*, 2009), thus, it required practice, supervision and/or more than one person to do the scoring. The rating scale was from St=1 (poor) to St=10 (good). The assessed parameters were aggregate size and shape, soil particles cohesion, aggregates and plough layer porosity, root development and soil surface dispersion. Over the years this method has been improved by several researchers in terms of the soil structure quality rating criteria and key parameters.

The Peerlkamp test was modified by changing the scale from ten to five structure quality rating scores, Sq1 (poor) – Sq5 (good) (Ball *et al.*, 2007). The key structural features assessed were the ease of break up, size and appearance of aggregates, visible porosity, and roots. Moreover, images of typical samples of varying soil types or different tillage systems on the same soil after break-up were included in each Sq score on the flowchart. It allowed the assessment of layers of contrasting soil structure within the spade depth then calculate the overall score (Ball *et al.*, 2007). This modified method was named Visual Soil Structure Quality Assessment (VSSQA) (Emmet-Booth *et al.*, 2016). The method by Ball and others (2007) was improved and renamed it Visual Evaluation of Soil Structure (VESS) (Figure 3.1a and b) (Guimarães *et al.*, 2011). The aim was to make VESS less subjective, quicker and easier to understand. It was recommended that data on soil penetration resistance, macro-porosity, biological aspect, bulk density and yield can be used to support the validity of the VESS thresholds to guide soil management. SubVESS (Figure 3.2a and b) method was established to assess the subsoil structure, which is an adjusted version of VESS with scale from Ssq1 (good) to Ssq5 (poor) (Ball *et al.*, 2015). Key diagnostic parameters for SubVESS are mottling, strength, porosity, pattern and depth of root penetration, and shape/size aggregate. The method called Double Spade (DS) which uses the principles of VESS and SubVESS was then developed (Emmet-Booth *et al.*, 2019). The visual assessment with this method is done to approximately 40 cm depth, providing additional information on soil structural quality below VESS depth (20 cm).

Individual layers are given separate scores between 1 (good) and 5 (poor) based on the penetration resistance, redox morphology, aggregate/fragment size, aggregate/fragment shape, intra-aggregate porosity, rapture resistance and rooting. VESS have been generally used and proven to be the simplest topsoil visual assessment methods compared to other methods such as Visual Soil Assessment (VSA) (Ball *et al.*, 2007; Guimarães *et al.*, 2013). The assessment of dynamic soil properties is usually done in the topsoil (20 – 30 cm) (Karlen *et al.*, 2003). This makes VESS a suitable tool to monitor the changes in soil structure quality, and SubVESS can then be used where the problem is suspected to extend to the lower depths below 30 cm. It was also indicated that if problems are identified when using a double spade (at 40 cm depth) SubVESS can be used for further assessment in the deeper parts of the profile (Emmet-Booth *et al.*, 2019).

3.5. Assessing soil structure quality using VESS in different soil types, land uses and management practices

The VESS method offers a current soil condition assessment and informed management decisions meant to improve or maintain soil quality (Ball *et al.*, 2017). Cherubin and others observed that VESS method is sensitive enough to detect changes in soil structural quality, therefore, the authors indicated its potential for direct in-situ examination (Cherubin *et al.*, 2017). It may be beneficial to use VESS together with a more detailed profile method to obtain an in-depth knowledge on the land use and soil management effect (Guimarães, Lamandé, *et al.*, 2017). On the other hand, SubVESS method has the potential to assess the effects of various management systems on the quality of soil structure (Obour *et al.*, 2017). This makes it a suitable profile method to be performed together with VESS. Visual evaluation of soil structure can be used to detect the structural quality changes of the soils under different arable management practices and land uses, however, texture appeared to be a problem (Askari *et al.*, 2013; Pulido Moncada *et al.*, 2017). Nonetheless, it has been shown that VESS method can assess changes in soil structural quality in a wide range of textures (Cherubin *et al.*, 2017).



Visual Evaluation of Soil Structure

Soil structure affects root penetration, water availability to plants and soil aeration. This simple, quick test assesses soil structure based on the appearance and feel of a block of soil dug out with a spade.
The scale of the test ranges from Sq1, good structure, to Sq5, poor structure.

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Equipment:

Garden spade approx. 20 cm wide, 22-25 cm long.
Optional: light-coloured plastic sheet, sack or tray ~50 x 80 cm, small knife, digital camera.

When to sample:

Any time of year, but preferably when the soil is moist.
If the soil is too dry or too wet it is difficult to obtain a representative sample.
Roots are best seen in an established crop or for some months after harvest.

Where to sample:

Select an area of uniform crop or soil colour or an area where you suspect there may be a problem. Within this area, plan a grid to look
at the soil at 10, preferably more, spots. On small experimental plots, it may be necessary to restrict the number to 3 or 5 per plot.

Method of assessment:

Step	Option	Procedure
Block extraction and examination		
1. Extract soil block	Loose soil	Remove a block of soil ~15 cm thick directly to the full depth of the spade and place spade plus soil onto the sheet, tray or the ground
	Firm soil	Dig out a hole slightly wider and deeper than the spade leaving one side of the hole undisturbed. On the undisturbed side, cut down each side of the block with the spade and remove the block as above.
2. Examine soil block	Uniform structure	Remove any compacted soil or debris from around the block
	Two or more horizontal layers of differing structure	Estimate the depth of each layer and prepare to assign scores to each separately.
Block break-up		
3. Break up block (take a photograph - optional)		Measure block length and look for layers. Gently manipulate the block using both hands to reveal any cohesive layers or clumps of aggregates. If possible separate the soil into natural aggregates and man-made clods. Clods are large, hard, cohesive and rounded aggregates.
4. Break up of major aggregates to confirm score		Break larger pieces apart and fragment it until a piece of aggregate of 1.5 - 2.0 cm. Look to their shape, porosity, roots and easily of break up. Clods can be broken into non-porous aggregates with angular corners and are indicative of poor structure and higher score.
Soil scoring		
5. Assign score		Match the soil to the pictures category by category to determine which fits best.
6. Confirm score from:		Factors increasing score:
	Block extraction	Difficulty in extracting the soil block
	Aggregate shape and size	Larger, more angular, less porous, presence of large worm holes
	Roots	Clustering, thickening and deflections
	Anaerobism	Pockets or layers of grey soil, smelling of sulphur and presence of ferrous ions
	Aggregate fragmentaion	Break up larger aggregates ~ 1.5 – 2.0 cm of diameter fragments to reveal their type
7.Calculate block scores for two or more layers of differing structure		Multiply the score of each layer by its thickness and divide the product by the overall depth, e.g. for a 25 cm block with 10 cm depth of loose soil (Sq1) over a more compact (Sq3) layer at 10-25 cm depth, the block score is (1 x 10)/25 + (3 x 15)/25 = Sq 2.2.

Scoring: Scores may fit between Sq categories if they have the properties of both.
Scores of 1-3 are usually acceptable whereas scores of 4 or 5 require a change of management.

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Figure 3.1 a: Visual Evaluation of Soil Structure (VESS) flowchart (Ball *et al.,* 2007; Guimarães *et al.,* 2011).

Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 **Friable** Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			 Fine aggregates	 The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 **Intact** Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil			 High aggregate porosity	 Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 **Firm** Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			 Low aggregate porosity	 Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 **Compact** Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			 Distinct macropores	 Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 **Very compact** Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			 Grey-blue colour	 Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

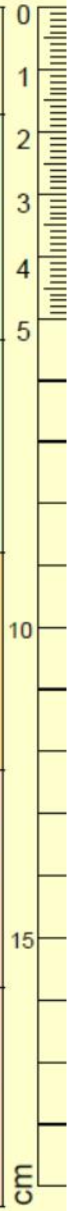
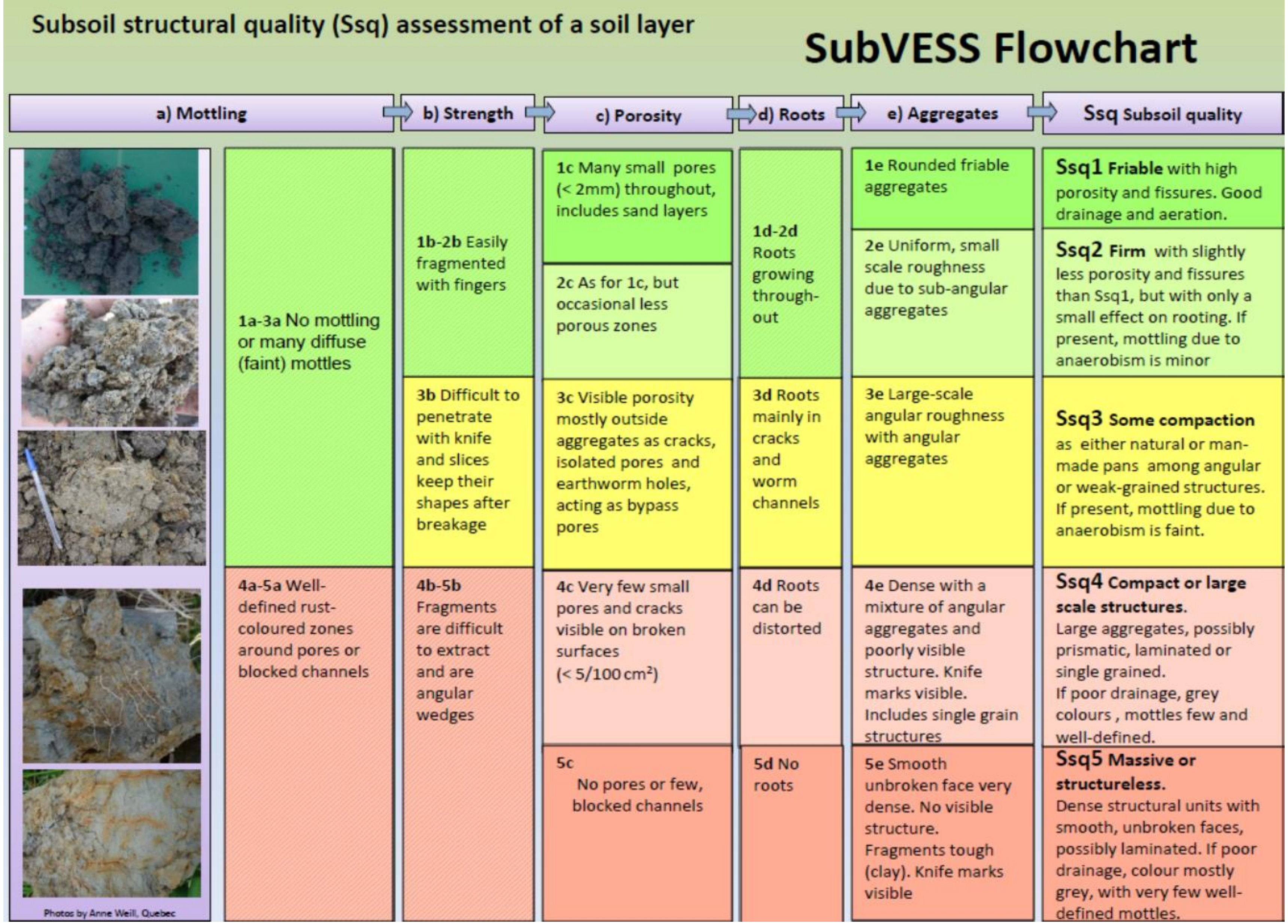


Figure 3.1b. Visual Evaluation of Soil Structure (VESS) flowchart (Ball *et al.*, 2007; Guimarães *et al.*, 2011).



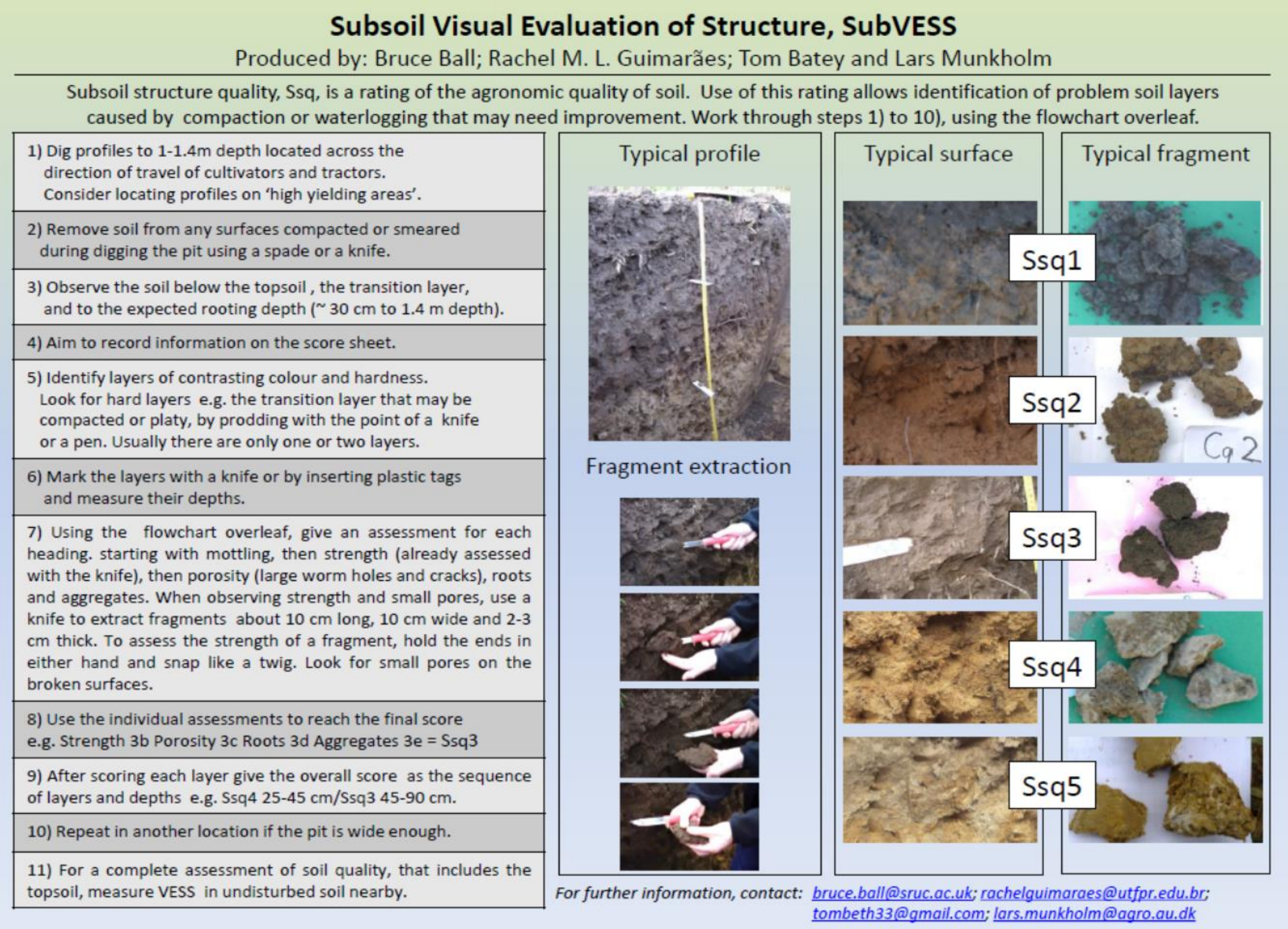
Subsoil structural quality (Ssq) assessment of a soil layer

SubVESS Flowchart

a) Mottling	b) Strength	c) Porosity	d) Roots	e) Aggregates	Ssq Subsoil quality
1a-3a No mottling or many diffuse (faint) mottles	**1b-2b** Easily fragmented with fingers	**1c** Many small pores (< 2mm) throughout, includes sand layers	**1d-2d** Roots growing through-out	**1e** Rounded friable aggregates	**Ssq1 Friable** with high porosity and fissures. Good drainage and aeration.
		2c As for 1c, but occasional less porous zones		**2e** Uniform, small scale roughness due to sub-angular aggregates	**Ssq2 Firm** with slightly less porosity and fissures than Ssq1, but with only a small effect on rooting. If present, mottling due to anaerobism is minor
	3b Difficult to penetrate with knife and slices keep their shapes after breakage	**3c** Visible porosity mostly outside aggregates as cracks, isolated pores and earthworm holes, acting as bypass pores	**3d** Roots mainly in cracks and worm channels	**3e** Large-scale angular roughness with angular aggregates	**Ssq3 Some compaction** as either natural or man-made pans among angular or weak-grained structures. If present, mottling due to anaerobism is faint.
4a-5a Well-defined rust-coloured zones around pores or blocked channels	**4b-5b** Fragments are difficult to extract and are angular wedges	**4c** Very few small pores and cracks visible on broken surfaces (< 5/100 cm²)	**4d** Roots can be distorted	**4e** Dense with a mixture of angular aggregates and poorly visible structure. Knife marks visible. Includes single grain structures	**Ssq4 Compact or large scale structures.** Large aggregates, possibly prismatic, laminated or single grained. If poor drainage, grey colours , mottles few and well-defined.
		5c No pores or few, blocked channels	**5d** No roots	**5e** Smooth unbroken face very dense. No visible structure. Fragments tough (clay). Knife marks visible	**Ssq5 Massive or structureless.** Dense structural units with smooth, unbroken faces, possibly laminated. If poor drainage, colour mostly grey, with very few well-defined mottles.

Photos by Anne Weill, Quebec

Figure 3.2a. Subsoil Visual Evaluation of Soil Structure (SubVESS) flowchart (Ball *et al.*, 2015).



Subsoil Visual Evaluation of Structure, SubVESS

Produced by: Bruce Ball; Rachel M. L. Guimarães; Tom Batey and Lars Munkholm

Subsoil structure quality, Ssq, is a rating of the agronomic quality of soil. Use of this rating allows identification of problem soil layers caused by compaction or waterlogging that may need improvement. Work through steps 1) to 10), using the flowchart overleaf.

1) Dig profiles to 1-1.4m depth located across the direction of travel of cultivators and tractors. Consider locating profiles on 'high yielding areas'.

2) Remove soil from any surfaces compacted or smeared during digging the pit using a spade or a knife.

3) Observe the soil below the topsoil , the transition layer, and to the expected rooting depth (~ 30 cm to 1.4 m depth).

4) Aim to record information on the score sheet.

5) Identify layers of contrasting colour and hardness. Look for hard layers e.g. the transition layer that may be compacted or platy, by prodding with the point of a knife or a pen. Usually there are only one or two layers.

6) Mark the layers with a knife or by inserting plastic tags and measure their depths.

7) Using the flowchart overleaf, give an assessment for each heading. starting with mottling, then strength (already assessed with the knife), then porosity (large worm holes and cracks), roots and aggregates. When observing strength and small pores, use a knife to extract fragments about 10 cm long, 10 cm wide and 2-3 cm thick. To assess the strength of a fragment, hold the ends in either hand and snap like a twig. Look for small pores on the broken surfaces.

8) Use the individual assessments to reach the final score e.g. Strength 3b Porosity 3c Roots 3d Aggregates 3e = Ssq3

9) After scoring each layer give the overall score as the sequence of layers and depths e.g. Ssq4 25-45 cm/Ssq3 45-90 cm.

10) Repeat in another location if the pit is wide enough.

11) For a complete assessment of soil quality, that includes the topsoil, measure VESS in undisturbed soil nearby.

Typical profile

Fragment extraction

Typical surface

Typical fragment

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Figure 3.2b. Subsoil Visual Evaluation of Soil Structure (SubVESS) flow chart (Ball *et al.*, 2015).

Furthermore, independent of soil texture visual assessments (including VESS and SubVESS) are effectively sensitive for identifying changes in soil structural quality (Lin *et al.*, 2022). Soil moisture status may influence the use of VESS to assess the structure more specifically the extraction of the soil slice and break-up (Guimarães *et al.*, 2011). Generally, the assessment can be done when the soil is moist but probably this can still be a challenge for soils with high clay percentage, the type of clay can also be problem. Since soils respond differently to applied pressure at different moisture content, it is always important to consider texture and moisture in the visual structure assessment.

VESS has been used to identify soil structural quality variation in different land uses (No-till and forest) with contrasting textures (clay and loam) (Giarola *et al.*, 2010). Guimarães and co-authors successfully used VESS to assess the quality of soil under five different land uses. VESS made it possible to identify changes in these land uses as compared to the quantitative measurements such as penetration resistance, total carbon and bulk density (Guimarães, Neves Junior, *et al.*, 2017). The study that was conducted using VESS and other visual soil evaluation methods (VSA and core VESS) showed that they are practical to detect soil structural quality changes in highly-weathered tropical soils due to land use differences (Cornelis *et al.*, 2019). The type of tillage system has an impact on the soil structural attributes. No-till and conventional tillage influences the soil bulk density, organic matter, aggregates, porosity, pH and CEC (Filho and Tessier, 2009). The number of VESS tests/sampling within a field should depend on the homogeneity and heterogeneity (Leopizzi *et al.*, 2018). Furthermore, the authors suggested five VESS tests to estimate the overall VESS score of a field or section of the field with homogeneous crop growth and a 0.5 minimum detectable change based on the in-field variability.

3.6. Visual soil structure assessment methods vs quantitative methods for determining structure quality related soil physical properties

There are direct and indirect methods (visual, field and laboratory) of determining the soil structure. The visual soil structure assessment methods are considered to be direct and give more details on its quality. There are several visual soil structure assessment methods including VESS that have been established and are receiving attention from farmers, extension officers, and researchers in some parts of the world

(Johannes, Weisskopf, *et al.*, 2017). These visual methods are semi-quantitative and have been proven to give valid information about soil structural quality. The assessment of key parameters such as porosity and aggregates strength, shape and size generates information on soil quality regarding water and air relations, plant growth, microorganisms and nutrient cycling (Guimarães, Lamandé, *et al.*, 2017). Visual soil assessment methods are poorly utilised in research because they are regarded as subjective and semi-quantitative (Rabot *et al.*, 2018). Visual soil structure quality assessment methods are beneficial as they complement laboratory analysis because they involve a number of different soil parameters (Pulido Moncada *et al.*, 2017). Scientifically, VESS is an important initial test for providing information on the overall soil quality (Ball *et al.*, 2017). Furthermore, it can be used to guide the soil sampling scales and sample types required.

X-ray micro Computed Tomography (µCT) is another laboratory method that is used to analyse the porosity of an undisturbed soil (Galdos *et al.*, 2019; Périard *et al.*, 2016; Taina *et al.*, 2008; Yang *et al.*, 2018) in order to provide information on soil structure and related properties such as hydraulic conductivity, bulk density and compaction. Soil bulk density and aggregate size distribution are some of the soil structure quality indicators that are determined in the laboratory (Rabot *et al.*, 2018). Aggregate size distribution and stability characterization is done both visually in the field and through laboratory methods such as wet sieving. However, it must be noted that the laboratory analyses are more precise than field visual assessments. There is a significant positive correlation between VESS method and quantitative soil physical parameters like bulk density, macro-porosity, soil water storage capacity index and penetration resistance (Cherubin *et al.*, 2017). The positive interaction occurs irrespective of the inherent soil properties such as texture and organic carbon. Visual soil structure methods have a moderate to good correlation with SOC, aggregate stability, bulk density, porosity, plant available water capacity and saturated and unsaturated hydraulic conductivity (Pulido Moncada *et al.*, 2014). Furthermore, it was discovered that there is a positive correlation between VESS and bulk density, macro-porosity, total porosity, aggregate stability and total organic carbon (Tuchtenhagen *et al.*, 2018). This is an indication of its (VESS) effectiveness and reliability to evaluate soil structure quality, therefore soil quality. SubVESS was also found to have a strong correlation with some laboratory quantitative methods (soil bulk density and porosity) for assessing soil compaction

(Obour *et al.*, 2017). This shows that it is a suitable tool to be operated together with VESS as it was developed to assess the subsoil. VESS and SubVESS are carried out together when soil structural problems especially those that will require further subsoil assessment such as porosity and pore network or connectivity are detected in the topsoil. This was supported by Lin and others who mentioned that SubVESS was developed to complement the original VESS, especially for soils subjected to compaction (Lin *et al.*, 2022). It is well known that compaction reduces soil porosity, more especially the macro porosity. In addition, have a negative impact on the pore connectivity which will in turn affect soil water and air permeability, micro-organisms and root growth.

There is usually impreciseness in both soil visual assessments and physical characterization (Johannes, Weisskopf, *et al.*, 2017), which may result from field conditions and/or human error. VESS has some advantages and disadvantages. The advantages are as follows: like other visual soil structure assessment methods VESS provide a judgement on structure quality at different states (Mueller *et al.*, 2009). Furthermore, it is rapid and with less soil disturbance. The integrated multiple degradation features and processes are performed directly in the field. VESS does not require extended training, specific equipment, or laboratory analyses and the results are immediately available (Johannes, Weisskopf, *et al.*, 2017). The ability of VESS to detect compaction damage was indicated as the major feature (Ball *et al.*, 2017). VESS has the capacity to differentiate layers with varying structural properties within the top soil (Cherubin *et al.*, 2017). The disadvantages are that the scores made by a single operator can be bias so there is a need for additional observers to do assessments (Ball *et al.*, 2007). The user might require training when using VESS for assessment and the same person should perform the evaluation to avoid scoring variability (Cherubin *et al.*, 2017). Laboratory measurements of the soil properties such as aggregate stability related to structure are expensive and time consuming. Generally, laboratory methods cannot provide an immediate and rapid soil structure quality assessment but are important for quantifying some features of soil structure (Ball *et al.*, 2007).

3.7. Conclusion

The VESS method has shown to be effective for assessing soil structural quality in routine soil characterisation. But, it must be noted that most soil structure attributes tend to be soil and site specific (Topp *et al.*, 1997). It is evident that non-experts can easily execute VESS. However, there is little research on the adoption of this method by the intended end users (land managers and farmers) in countries or areas where it was tested. Thus, there is a need to report on the adoption and the impact the VESS method has in soil management and conservation. We have noted that the subjectivity of the VESS method will remain a challenge in the broader community of land users especially for the beginners. On the other hand, it is much easier for the researchers because of their background in soil science. However, with proper training the non-experts such as farmers can do the assessment independently and efficiently. So, soil scientists should reach out to farmers and land managers to facilitate the use of the VESS method so that it can be incorporated in soil quality assessment for good management and conservation.

Future research should aim at improving and incorporating faunal assessments in visual methods and the proof of their contribution in soil structure dynamics (Guimarães, Lamandé, *et al.*, 2017). There should be an optimum soil moisture content range specifically for VESS (Guimarães, Neves Junior, *et al.*, 2017) depending on soil conditions because it could affect the assessment outcome. It will still be necessary for field or laboratory quantitative data to obtain an in-depth information on the nature of soil structure particularly where the VESS assessment indicates poor structural quality. Furthermore, there could be some guidelines on the type of management practices to be implemented for amelioration based on the overall results (VESS and field/laboratory measurements) for specific land uses e.g. crop land, pasture, or timber. More research is also required on the assessment frequency or intervals for monitoring.

CHAPTER 4

UNEARTHING SOIL STRUCTURE DYNAMICS UNDER LONG-TERM NO-TILLAGE SYSTEM IN CLAYEY SOILS

Abstract

Soil structure is a sensitive and dynamic soil physical property that responds rapidly to different tillage systems, and thus it requires constant monitoring and evaluation. The visual evaluation of soil structure (VESS) and subsoil visual evaluation of soil structure (SubVESS) methods were used to assess the soil structure quality of clayey soils subjected to different tillage systems. The tillage systems were no-tillage (NT) and conventional tillage (CT), with virgin fields (VGs) used as controls. The study was conducted at Tshivhilwi and Dzingahe in Thohoyandou, Vhembe District, Limpopo Province, South Africa. The soil structure quality at Tshivhilwi, as determined by VESS and SubVESS, was found to be poor. However, at Dzingahe, both the VESS and SubVESS scores responded to the impact of tillage. VESS showed a fair (Sq = 2.25) soil structural quality in the NT system, poor quality (Sq = 3.57) in the CT system and moderately poor quality (Sq = 3.05) in the VG. Similarly, at the same location, the SubVESS scores were moderately good in the NT system, moderately poor for the CT system and fair in the VG. The differences in the responses of VESS and SubVESS at the two locations were attributed to differences in the duration of the NT system. The VESS and SubVESS results were supported by selected measured soil physico-chemical properties such as bulk density and porosity. In conclusion, the findings of this study showed that VESS and SubVESS were able to effectively differentiate between the impacts of tillage systems on soil structural quality. The soil structure quality was better under NT than CT at Tshivhilwi and Dzingahe.

Key words: tillage; texture; VESS; SubVESS; structure

4.1. Introduction

Soil structure is a sensitive and dynamic soil physical property. It rapidly responds to management practices, land use changes, moisture and temperature regimes (Yudina and Kuzyakov, 2023). As a result, it requires frequent assessment and monitoring. It is most regularly assessed when evaluating soil quality under various tillage systems and land uses (Pulido Moncada *et al.*, 2014) and is regarded as a general soil quality indicator (Ball *et al.*, 2017). Soil tillage systems are the major contributors to soil structural modifications (Li *et al.*, 2019; Liu *et al.*, 2021; Pires *et al.*, 2017; Tian *et al.*, 2022). The resultant soil structure can influence other soil properties such as aeration, water retention, availability and movement. Therefore, assessing soil structural quality is a key component of soil quality monitoring and assessment (Leopizzi *et al.*, 2018).

Traditional methods used for quantifying soil structural parameters are generally expensive as they need complicated equipment. They are also time consuming and require an in-depth knowledge of soil science. Furthermore, soil structure is commonly characterised qualitatively on the basis of class, grade and type (Diaz-Zorita *et al.*, 2002), which lacks detail on its quality. Considering these challenges, semi-quantitative visual soil structure evaluation methods can provide a more detailed assessment.

The primary visual methods of assessing soil structure focus on describing rooting, soil aggregates and porosity (Ball *et al.*, 2017). One of them is the visual evaluation of soil structure (VESS). The VESS method was developed to assess soil structural quality using a description chart to compare aggregate and root features to assign a soil quality score (Guimarães, Neves Junior, *et al.*, 2017). VESS scores reflect the effect of agricultural management practices such as tillage on soil quality (Askari *et al.*, 2013). Numerous methods developed for topsoil visual assessment, like VESS, put more emphasis on compaction status (Ball *et al.*, 2015). Where necessary, SubVESS can be used to assess the subsoil structural quality. VESS has been validated in its application together with some soil physical, chemical and biological properties and has proven to be effective in assessing soil structure quality and therefore soil quality (Cherubin *et al.*, 2017; Emmet-Booth *et al.*, 2020; Pulido Moncada *et al.*, 2014; Purnama *et al.*, 2022; Ramos *et al.*, 2022; Tuchtenhagen *et al.*, 2018). VESS can enable farmers and land users to frequently assess and monitor soil quality as it is cheap, easy to execute and rapid. Despite their reported effectiveness, neither VESS nor SubVESS are commonly used in South Africa and have not been tested enough, especially on subtropical clayey soils.

Conservation (i.e., no-tillage) and conventional tillage systems may alter soil structure regardless of the texture. Tillage systems gradually modify soil physical properties, which can lead to increased soil compaction (Martins *et al.*, 2021). Conventional tillage temporarily encourages larger soil pores than a no-tillage system, especially in the topsoil layer (Fernandes *et al.*, 2023). Soil structural changes that result from conventional soil preparation affect bulk density, porosity, water retention and storage, aeration and aggregate stability (Filho and Tessier, 2009). The no-tillage system, over time, can also have a negative or positive impact on some of these parameters. The adoption of no-tillage has challenges such as soil compaction and the stratification of organic matter (Topa *et al.*, 2021). There is variability in the execution of these tillage systems, more especially for no-tillage; hence their impacts are not always the same.

The main purpose of this study was to assess the impact of long-term no-tillage system on soil structure quality in clayey soils. The study hypothesises that (i) the structural quality and parameters of clayey soils vary significantly across different tillage systems; and (ii) a tillage system has the same impact on soil structural quality and parameters at different locations.

4.2. Materials and Methods

4.2.1. Site Description

The study was carried out at two locations in Thohoyandou, Vhembe district, Limpopo province, South Africa. Location 1 was at Tshivhilwi (22°50′54″ S, 30°38′38″ E, 512 m above sea level), where the no-tillage field was 6 ha, with maize planted throughout the year in rotation with sugar beans, tepary beans, spinach, swiss chard, mustard spinach and cabbage under irrigation. Maize was the only crop cultivated in the conventional tillage field once a year under rainfed. Location 2 was at Dzingahe (22°55′32″ S, 30°31′00″ E, 662 m above sea level); the no-tillage field was 2 ha, with the main crops being maize and ground nuts, which were intercropped and planted only during the rainy season under rainfed conditions. Maize was the only crop cultivated in the conventional tillage field and also planted only during the rainy season under rainfed. The virgin fields at both locations were not cultivated; however, livestock belonging to the local community were allowed to graze. The frequency and intensity of grazing were unknown as the livestock were not managed or controlled. Furthermore, the virgin fields were open and the livestock were not enclosed, which allowed them to move freely. The no-tillage fields in Tshivhilwi and Dzingahe had been untilled for 8 and 40+ years, respectively, while the number of years of tillage of the conventional tillage fields was estimated to be about 50 years. The clay% was ranging between 30.53 – 41.47% and 26.53 – 48.93% at Tshivhlwi and Dzingahe respectively. Both study sites had an average annual rainfall of 762 mm, a minimum temperature of 15 °C and a maximum temperature of 28 °C.

4.2.2. Soil Sampling

Soil samples were collected from no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi and Dzingahe. The VG was used as a control treatment at each location. Five sampling points were randomly selected in a portion (area = 1000 m^2) of each field per location considering the homogeneity of the soil. Soil samples were dug up at the selected sampling points. The sampling depths were 0–30 cm and 30–60 cm. A total of 60 soil samples (30 topsoil and 30 subsoil) were collected from both locations. Visual (i.e., VESS and SubVESS) methods were used to assess soil structure quality in the field, and other selected soil parameters were also analysed in the laboratory to validate the outcome of the visual observations.

4.2.3. VESS and SubVESS

Visual assessment of soil structure quality in the field was carried out with the VESS (Ball *et al.*, 2007; Guimarães *et al.*, 2011) and SubVESS (Ball *et al.*, 2015) methods. First, the VESS was carried out. Then, a soil pit (1 m × 1 m × 0.7 m) was dug for the SubVESS assessment. The VESS method was used to assess soil structure in the topsoil (0–30 cm) based on the key parameters, namely, aggregates, porosity and roots. Then, a score rating from Sq1 to Sq5 (Sq1–2 = good, Sq2–3 = fair, Sq3–Sq5 = poor) was assigned. The SubVESS method was used to assess soil structure in the subsoil (30–60 cm) based on key parameters, namely, mottling, strength, porosity, roots and aggregates. Then, a score rating from Ssq1 to Ssq5 (Ssq1–3 = good, Ssq4 = fair, Ssq5 = poor) was assigned.

4.2.4. Data Collection

Soil bulk density (BD) was determined by collecting samples with stainless steel cylindrical core samplers with an internal diameter of 5 cm and 5 cm height from each field at the 0–30 cm and 30–60 cm depths. The cylindrical cores were used to measure the bulk density as the mass in grams of the oven-dried soil per volume of core in cubic centimetres. The bulk density was then calculated using the obtained oven-dried mass of each sample and the volume of the core (Jabro *et al.*, 2016). After calculating the BD, the pore percentage was then calculated using the bulk density values with the following formula: %porosity = $\left[1 - \frac{Bulk\ density}{Particle\ density}\right] \times 100$; a particle density of 2.65 g/cm^3 was used. Particle size distribution was determined by the Bouyoucos method (Bouyoucos, 1962). Soil organic carbon was analysed using the Walkley and Black method (Meersmans *et al.*, 2009). Soil pH was measured with a pH meter model (Lab 845 Set/BL19 pH) in a 1:2.5 (v/v) soil: water and soil: KCl solution suspensions. Soil electrical conductivity (EC) was measured (Lab 945 Set/LF435T) in a 1:2.5 (v/v) soil: water suspension *(Okalebo et al*., 2002).

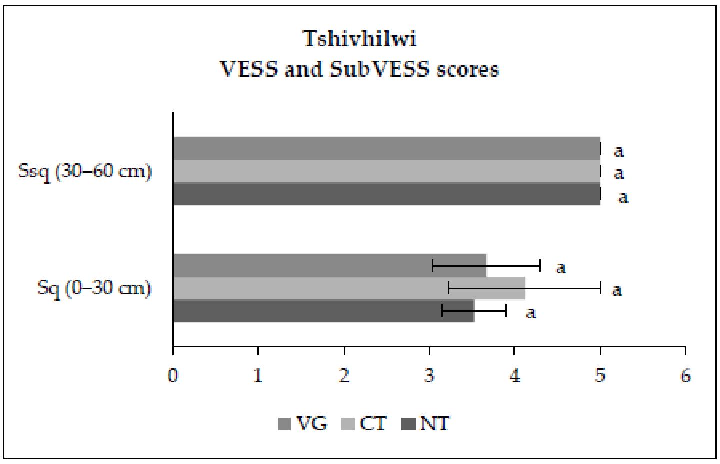
4.2.5. Statistical Analysis

The collected data were subjected to analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) at a 95% confidence interval ($p \leq 0.05$) to compare the parameters measured between the tillage systems at each location using IBM SPSS statistics 29.0 statistical software. The Pearson correlation coefficient was used to check the relationship between the parameters at each location. The means of the measured parameters in the same tillage systems at the different locations were compared only using MANOVA.

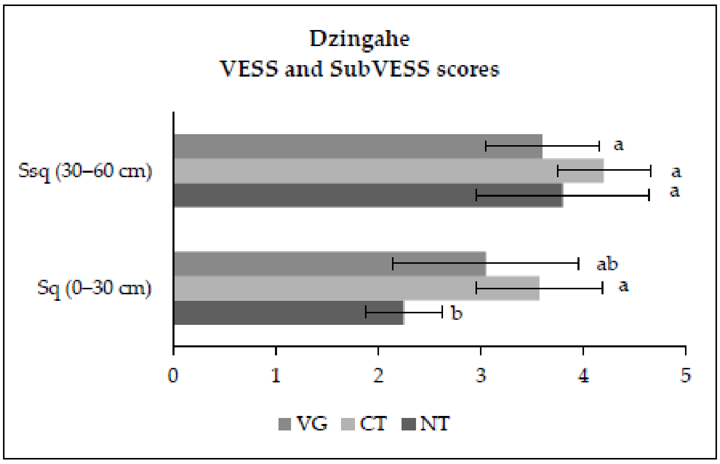
4.3. Results

4.3.1. VESS and SubVESS as Influenced by Tillage System

At Tshivhilwi, the VESS (Sq) and SubVESS (Ssq) scores did not show any significant differences between the tillage systems. The soil structure quality was poor for all the tillage systems (NT: Sq = 3.53; CT: Sq = 4.12; VG: Sq = 3.67). Even though no significant differences were observed, NT had the lowest Sq score and CT had the highest. The SubVESS (Ssq) scores were also poor, with an equal score of 5 for all the tillage systems (Figure 4.1a). At Dzingahe, the VESS (Sq) scores varied significantly ($p = 0.009$) between NT and CT but there was no significant difference between the NT and VG or between the CT and VG tillage systems. The topsoil structure quality was fair (Sq = 2.25) for NT and poor for CT (Sq = 3.57) and VG (Sq = 3.05). The SubVESS (Ssq) scores did not show a significant difference between the tillage systems. Subsoil structure quality was moderately good for NT (Ssq = 3.80) and VG (Ssq = 3.60) and moderately poor for CT (Ssq = 4.20) (Figure 4.1b). Topsoil structure quality was better in NT than CT at both locations. Overall, the tillage systems did not have a significant effect on the soil structure quality except VESS ($p = 0.03$) at Dzingahe.



(a)

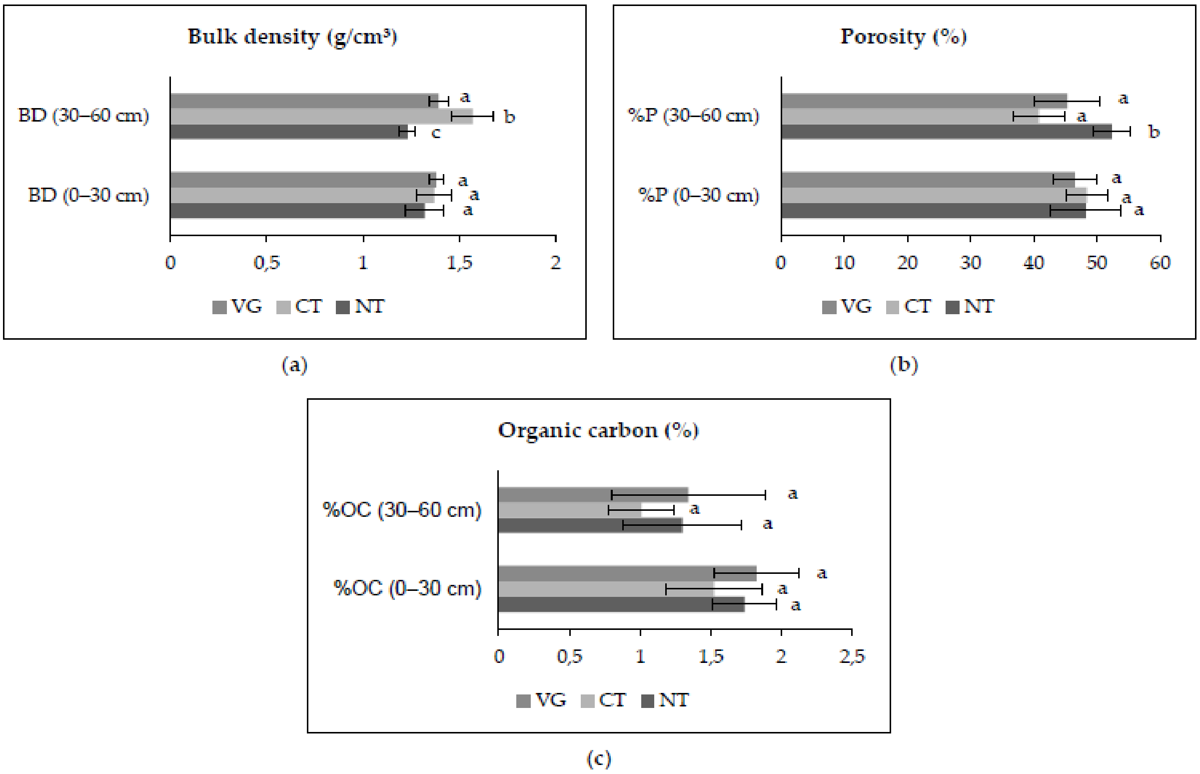


(b)

Figure 4.1 (a,b): VESS and SubVESS assessment under different tillage systems at Tshivhilwi and Dzingahe. Sq = VESS score, Ssq = SubVESS score, NT = no-tillage, CT = conventional tillage, VG = virgin field. The letters a and b indicate significant difference.

4.3.2. Soil physico-chemical properties

At Tshivhilwi, the bulk density (BD) and porosity showed no significant differences between the tillage systems in the 0–30 cm soil depth. No-tillage had the lowest (1.32 g/cm^3) and CT the highest (1.38 g/cm^3) value. On the other hand, BD varied significantly between NT and CT ($p \leq 0.001$), between NT and VG ($p = 0.004$) and between CT and VG ($p = 0.002$) in the 30–60 cm soil depth. Conventional tillage had the highest BD (1.57 g/cm^3) value, followed by VG (1.39 g/cm^3), and the lowest value was seen in NT (1.23 g/cm^3); therefore, NT was less compacted than CT but both bulk densities were low (Figure 4.2a). The pore percentage ranged from 46.56 to 48.43% in the 0–30 cm soil depth. In the 30–60 cm soil depth, porosity indicated a significant difference ($p < 0.05$) between NT and CT and between NT and VG. No-tillage had the highest porosity (52.38%), followed by VG (45.35%), and the lowest porosity was seen in CT (40.81%) (Figure 4.2b). Organic carbon (OC) was non-significant in all the tillage systems in both soil depths. However, VG had the highest OC in both depths, followed by NT, and CT had the lowest score. The values ranged from 1.52 to 1.82% in the 0–30 cm soil depth and from 1.01 to 1.34% in the 30–60 cm soil depth (Figure 4.2c). The pH (water and KCl) was acidic (6.52–6.67 and 5.10–5.42, respectively) in all the tillage systems in the 0–30 cm soil depth, whereas in the 30–60 cm soil depth it ranged from acidic to slightly alkaline (5.45–5.67 and 6.71–7.22, respectively). The electrical conductivity ranged from 0.24 to 0.34 mS/cm for the 0–30 cm and from 0.20 to 0.32 mS/m for the 30–60 cm soil depth, and the soils were non-saline (Table 4.1).



(a) (b)

(c)

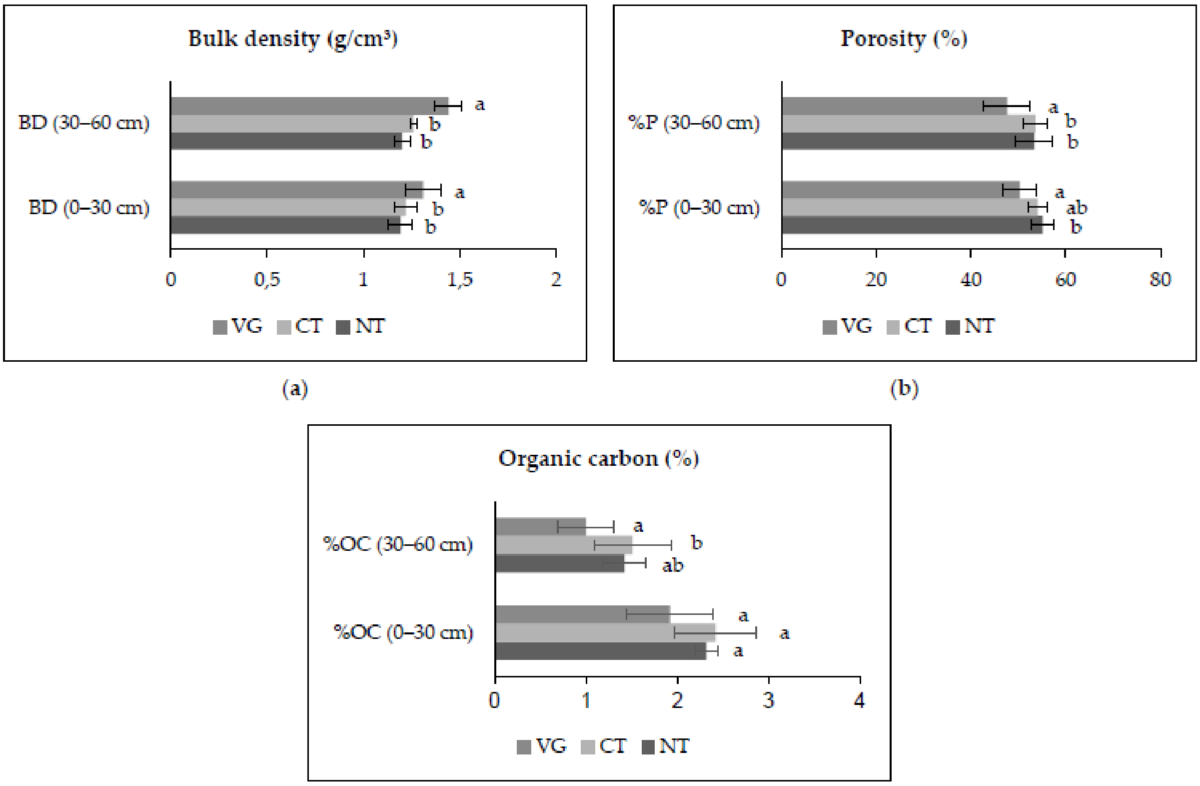
Figure 4.2 (a–c): Soil bulk density (BD), porosity (%P) and organic carbon (OC) measurements under different tillage systems at Tshivhilwi. Sq = VESS score, Ssq = SubVESS score, NT = no-tillage, CT = conventional tillage, VG = virgin field. The letters a, b and c indicate significant difference.

Table 4.1. Soil pH (KCl), pH (W) and electrical conductivity (EC) under no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi.

Tillage System	**pH (KCl)**	**pH(W)**	**EC (mS/cm)**
	Soil depth (0–30 cm)		
NT	5.42 (0.53)	6.67 (0.55)	0.34 (0.13)
CT	5.10 (0.28)	6.52 (0.35)	0.16 (0.05)
VG	5.18 (0.43)	6.55 (0.50)	0.24 (0.09)
	Soil depth (30–60 cm)		
NT	5.67 (0.55)	7.07 (0.50)	0.25 (0.15)
CT	5.45 (0.40)	6.71 (0.36)	0.20 (0.12)
VG	5.46 (0.36)	7.22 (0.42)	0.32 (0.13)

pH(KCl) = pH in potassium chloride solution, pH(W) = pH in water. The values in brackets are standard deviations (SD).

At Dzingahe, BD differed significantly between NT and VG and between CT and VG in the 0–30 cm and 30–60 cm soil depths. In the 0–30 cm soil depth, the virgin field had the highest BD (1.32 g/cm^3), followed by CT (1.22 g/cm^3), while NT (1.19 g/cm^3) had the lowest. The same trend was observed in the 30–60 cm soil depth, with VG the highest (1.44 g/cm^3), followed by CT (1.26 g/cm^3) and NT (1.20 g/cm^3) (Figure 4.3a). So, the soils in all the tillage systems and both depths were not compacted. However, NT was less compacted than CT. Porosity varied significantly between NT and VG (p = 0.02) in the 0–30 cm soil depth and between NT and VG (p = 0.04) and CT and VG (p = 0.03) in the 30–60 cm soil depth. No-tillage had the highest porosity (55.10%) and VG (50.35%) had the lowest in the 0–30 cm soil depth. NT (53.31%) and CT (53.62%) varied slightly but had a greater porosity compared to VG (47.65%) in the 30–60 cm soil depth (Figure 4.3b). Organic carbon differed significantly between CT and VG (p = 0.03) in the 30–60 cm soil depth only. Conventional tillage (2.42% and 1.51%) had the highest OC, followed by NT (2.32% and 1.42%), and VG (1.92% and 1.00%) had the lowest OC in both depths (Figure 4.3c). OC decreased with depth as expected, because topsoils usually contains more OC than subsoils. The pH (water and KCl) was acidic (6.18–6.53 and 4.64–5.33) in all the fields and depths, while the electrical conductivity showed that the soils were non-saline (0.20–0.24 and 0.16–0.22 mS/cm) (Table 4.2). Generally, the tillage systems did not have a significant effect on the measured physico-chemical properties at Tshivhilwi. However, at Dzingahe, they were significantly ($p = 0.02$) affected by the tillage systems. There were notable effects on individual soil properties that could have resulted from the specific type of tillage system.



(a) (b) (c)

Figure 4.3 (a–c): Soil bulk density (BD), porosity (%P) and organic carbon (OC) measurements under no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Dzingahe. The letters a and b indicate significant difference.

Table 4.2**.** Soil pH(KCl), pH(W) and electrical conductivity (EC) under no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Dzingahe.

Tillage System	**pH (KCl)**	**pH (W)**	**EC (mS/cm)**
Soil depth (0–30 cm)			
NT	4.89 (0.08)	6.23 (0.11)	0.20 (0.07)
CT	5.10 (0.31)	6.37 (0.24)	0.24 0.05)
VG	4.77 (0.31)	6.18 (0.23)	0.20 (0.10)
Soil depth (30–60 cm)			
NT	5.06 (0.24)	6.40 (0.29)	0.16 (0.09)
CT	5.33 (0.40)	6.53(0.29)	0.22 (0.04)
VG	4.64 (0.37)	6.41(0.36)	0.20 (0.07)

pH(KCl) = pH in potassium chloride solution, pH(W) = pH in water. The values in brackets are standard deviations.

4.3.3. Pearson correlations among the soil physico-chemical properties at Tshivhilwi and Dzingahe

At Tshivhilwi, the VESS score correlation with BD (r = 0.13), OC (r = 0.14), silt (r = 0.08) and sand (r = 0.06) in the 0–30 cm soil depth was positive. A very weak negative correlation of the VESS score with porosity (r = -0.09) and clay (r = -0.10) was found in the same soil depth. The negative correlation of BD with clay (r = -0.12) and sand (r = -0.12) in the 0–30 cm soil depth was very weak; however, there was a highly significant and strong negative correlation between porosity and BD (r = -0.72) in the same soil depth. Bulk density in the 30–60 cm soil depth also showed a significantly strong negative and moderate positive correlation with porosity (r = 0.87) and silt (r = 0.53), respectively. Sand showed a weak positive correlation with porosity (r = 0.16) in the 0–30 cm soil depth. A very weak negative correlation of porosity with OC (r = -0.09), clay (r = -0.07) and silt (r = -0.02) was observed in the 0–30 cm soil depth. Porosity showed a significant moderate positive and negative correlation with clay (r = 0.63) and silt (r = -0.59) in the 30–60 cm soil depth, respectively. However, sand in this depth showed a very weak negative correlation with porosity (r = -0.12).

At Dzingahe, there was a highly significant moderate positive correlation between the VESS and SubVESS scores (r = 0.62). VESS had a weak positive correlation with BD (r = 0.33), OC (r = 0.23), clay (r = 0.12) and sand (r = 0.07), whereas a weak negative correlation was observed with porosity (r = -0.34) and silt (r = -0.30) in the same depth. A very weak positive correlation of the SubVESS score with clay (r = 0.004) and sand (r = 0.05) was found, while BD (r = -0.02), porosity (r = -0.14), OC (r = -0.01) and silt (r = -0.07) showed a very weak negative correlation with the SubVESS scores in the same soil depth. The correlation between BD and porosity (r = -1.00) in the 0–30 cm soil depth was very strong and highly significant. There was a very weak positive correlation between BD and sand (r = 0.04) in the 0–30 cm soil depth, but OC (r = -0.03), clay (r = -0.02) and silt (r = -0.03) showed a very weak correlation with BD in the same soil depth. Bulk density in the 30–60 cm soil depth correlated negatively and significantly with porosity (r = -0.68) and OC (r = -0.54). The negative correlation of BD with clay (r = -0.10) and silt (r = -0.14) was weak. Only sand showed a very weak positive correlation with BD (r = 0.26) in the same depth. A very weak positive correlation of porosity with OC (r = 0.04), clay (r = 0.02) and silt (r = 0.02) was observed, along with a very weak negative correlation with sand (r = -0.03), in the 0–

30 cm soil depth. Porosity in the 30–60 cm soil depth indicated a weak positive correlation with OC ($r = 0.21$) and silt ($r = 0.45$), while the correlation with clay ($r = -0.10$) and sand ($r = -0.18$) was weakly negative.

4.3.4. Comparison of soil physico-chemical properties under the same tillage systems between Tshivhilwi and Dzingahe.

The physico-chemical soil properties under the respective tillage systems were generally not affected by the study site. However, significant differences were identified in some soil properties under similar tillage systems between Tshivhilwi and Dzingahe. Bulk density ($p = 0.004$), porosity ($p = 0.04$), organic carbon ($p = 0.01$) and clay content ($p = 0.03$) in the 0–30 cm soil depth and structure quality (VESS and SubVESS) ($p \leq 0.001$ and $p = 0.01$, respectively) showed significant difference between the NT fields. The topsoil structure quality was poor (Sq = 3.53) at Tshivhilwi and fair (Sq = 2.52) at Dzingahe. The subsoil structure quality was poor (Ssq = 5) at Tshivhilwi and moderately fair (Ssq = 3.80) at Dzingahe (Figure 4.4). Dzingahe also showed a lower bulk density (1.19 g/cm3) than Tshivhilwi (1.32 g/cm3) (Figure 4.5), but the clay content (37.60%) was greater at Tshivhilwi than at Dzingahe (26.53%). Porosity and organic carbon were relatively higher at Dzingahe (55.10% and 2.32%, respectively) than at Tshivhilwi (48.28% and 1.74%, respectively).

It was also found that bulk density ($p = 0.013$ and $p \leq 0.001$), porosity ($p = 0.013$ and $p \leq 0.001$) and organic carbon ($p = 0.007$ and $p = 0.048$) in both soil depths (0–30 cm and 30–60 cm) and subsoil structure quality showed significant difference between the conventional tillage fields. The SubVESS scores indicated a poor structure quality at Tshivhilwi (Ssq = 5.00) and Dzingahe (Ssq = 4.20) (Figure 4.4). Bulk density was highest at Tshivhilwi (1.37 g/cm^3 and 1.57 g/cm^3) than at Dzingahe (1.22 g/cm^3 and 1.26 g/cm^3) (Figure 4.5). Dzingahe (54.09% and 53.62%) had higher porosity than Tshivhilwi (48.43% and 40.81%). Organic carbon was also higher at Dzingahe (2.42% and 1.51%) than at Tshivhilwi (1.52% and 1.01%). Subsoil structure quality was the only parameter that varied significantly ($p \leq 0.001$) between the virgin fields: it was poor (Ssq = 5.00) at Tshivhilwi but good (Ssq = 3.60) at Dzingahe.

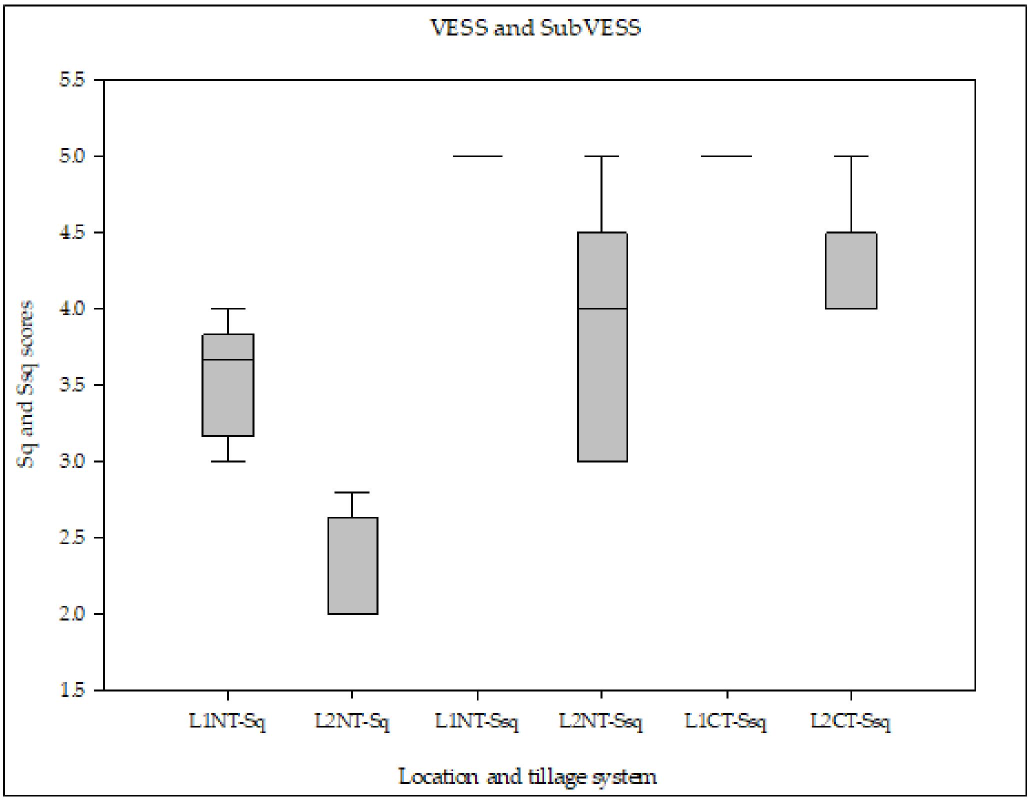


Figure 4.4: VESS (Sq) and SubVESS (Ssq) scores under no-tillage (NT) and conventional tillage (CT) systems at Tshivhilwi (L1) and Dzingahe (L2).

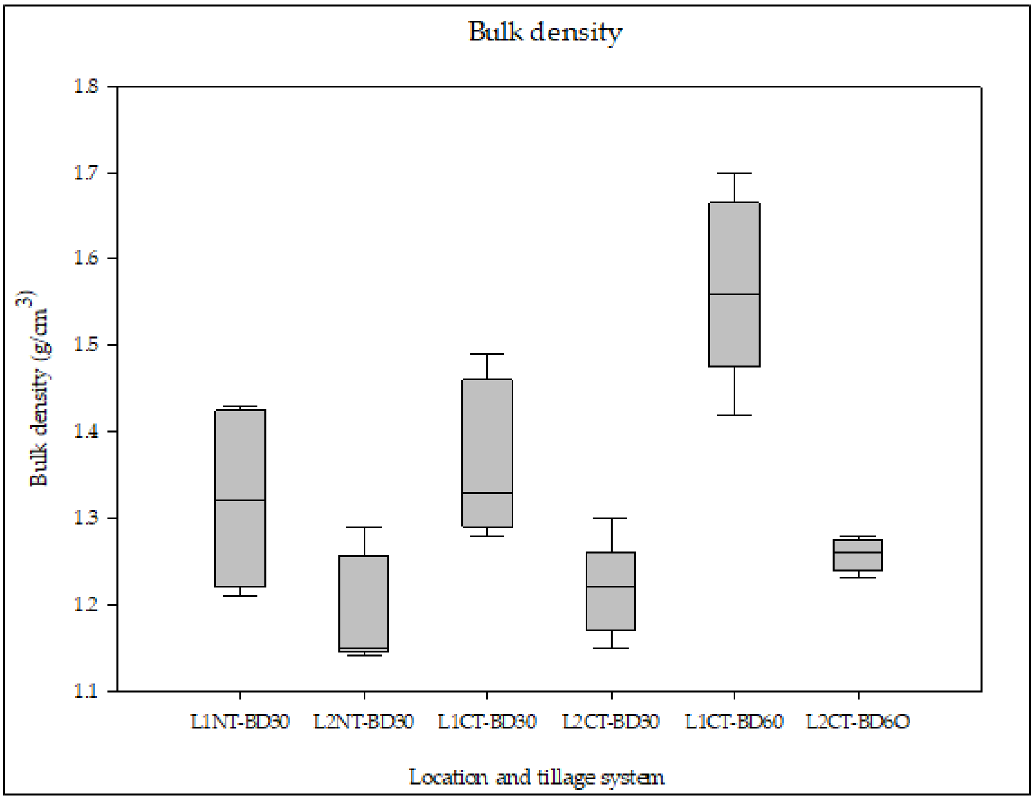


Figure 4.5: Bulk density (BD) under no-tillage (NT) and conventional tillage (CT) systems at Tshivhilwi (L1) and Dzingahe (L2). BD30 = bulk density in the 0–30 cm soil depth, BD60 = bulk density in the 30–60 cm soil depth.

4.4. Discussion

The soil structure quality at Dzingahe was found to be better than that at Tshivhilwi when compared across the tillage systems. The results suggested that the tillage systems did not exclusively alter the soil structure but other practices such as cropping systems and residue management could have contributed to the changes (Abdollahi *et al.*, 2015; Askari *et al.*, 2013; Panday and Nkongolo, 2021). It was observed that the tillage systems were not practised in the same way in these two locations and that the duration of NT was also different, with a gap of more than 30 years. No-tillage at Tshivhilwi had been active for 8 consecutive years, while at Dzingahe it had been practised for more than 40 years. The visual assessment with VESS and SubVESS indicated that the soil structure quality was good at Dzingahe and moderate to poor at Tshivhilwi. This could be attributed to the duration of NT and also to the intensity of the activities at Tshivhilwi, as the field is utilized throughout the year, while at Dzingahe the field is planted once a year during the rainy season. It was clear that the degree of the impact of these tillage systems on the soil structure was different. However, both NT and CT can result in soil structural damage or improvement depending on their management (Blanco-Canqui and Ruis, 2018; Tuzzin de Moraes *et al.*, 2016). The VESS and SubVESS scores indicated a better soil structure quality under NT than under CT at both locations. This could be due to the operations carried out in the respective tillage systems, especially the lower soil disturbance in NT (Askari *et al.*, 2013; Cooper *et al.*, 2021). Bulk density (BD) values were also shown to be lower in NT than in CT, which was similar to the discovery of (Alletto *et al.*, 2022).

The specific effects of no-tillage and conventional tillage systems on the soil structure could depend on the soil texture, mainly the amount and type of clay present, which might be the case at the study sites of this research. This was also identified by (Franco *et al.*, 2019). The authors showed that fine soils scored higher than coarse soils. The results suggest that, over time, both NT and CT can lead to deterioration or improvement of the soil structure quality at different soil depths, depending on how they are executed (Li *et al.*, 2019; Tian *et al.*, 2022). The common problem in NT is the topsoil compaction that occurs over time (Fernández-Ugalde *et al.*, 2009), which can cause damage to the soil structure and affect permeability. However, the structural damage can be severe under CT because the soil is mechanically turned and aggregates are destroyed during seedbed preparation. Soil compaction under CT generally happens below the plough layer (±25 cm). Hence, the bulk density in the subsoil was higher than in the topsoil, although this did not indicate that the soil was compacted. The clay content of the soil, together with the tillage systems in the cultivated fields, could have contributed extensively to the nature of the soil structure in the top 30 cm. The virgin fields also exhibited poor soil structure at both locations, which may be attributed to inherent properties like texture and/or to some extent the impact (i.e. overgrazing) of the grazing animals. Animals can damage soil structure through compaction when they move around and graze the field. In addition, they can also make the soil surface bare in some parts if they overgraze, thus exposing the soil to further structural damage and carbon loss. Hence, VG indicated a lower OC than CT and NT at Dzingahe, however, this was not the case at Tshivhilwi because VG had a greater OC than the two tillage systems. These differences could have been attributed to by the type of the vegetation cover and the intensity of grazing and the quantity of the animals. The higher BD in both VG and CT than NT could have also contributed to the OC content, furthermore, affected the porosity. Porosity play an important role in soil aeration and water relations which also contribute largely to organic carbon turn over. It is important to note that the clay percentage of the soil tend to control the dynamics of these parameters. In addition, the results in the two study sites were different which furthers shows that the respective activities in the tillage systems and virgin fields determine their apparent soil structure quality.

The structural variation between the 0–30 cm and 30–60 cm soil depths was logical and could have been caused by higher clay content and lower organic matter in the subsoil, which is in agreement with the findings of (Obour *et al.*, 2017). Obour and others found that clay content had a strong effect on mottling in the 20–45 cm soil depth and on aggregates and rooting in the 45–65 cm soil depth. Mottling was mostly identified in the 30–60 cm soil depth, although in some pits at Tshivhilwi it was evident in the 0–30 cm soil depth. Mottling, which refers to patches of colour mixed with the dominant soil colour, is generally caused by poor soil aeration and drainage. The poor air and water permeability of the soil is a result of reduced macroporosity, which is common in soils with a high clay content and/or that are compacted. These clay and/or compacted soils tend to have poor soil structure. It was found that clay content had more effect than compaction on the soil structure. As such, where the clay content was high, the VESS and SubVESS scores were also high. Alternatively, where the clay content was low, the VESS and SubVESS scores were also low. However, soil bulk density was shown to have minor divergence with the VESS and SubVESS scores. It was inconsistent between the fields in both soil depths and locations.

The VESS scores showed a weak positive and negative relationship with bulk density and porosity, respectively, at both locations. Cherubin *et al.* (2017) discovered almost similar results, where bulk density correlated positively with VESS scores. The authors further indicated VESS scores were related to an increase in bulk density, which may cause a reduction in macroporosity, increased water retention and reduced permeability. Purnama *et al.* (2022) found a strong relationship between VESS scores and bulk density, porosity and organic carbon. It was also observed in this study that the poor soil structure as assessed by VESS cannot be due to compaction, as the BD values were within the normal range (Rivenshield and Bassuk, 2007). Although, VESS and SubVESS did not show significant correlation with other soil parameters whether positive or negative, the quantitative results validated the effectiveness and reliability of these visual methods. It is worth noting that the visual assessment is based on the scale which to some level may not record the smallest units (especially SubVESS) which contribute to the differences in the quantitative data. However, as it was mentioned, the correlation analysis corroborated the effectiveness of VESS and SubVESS. Given the clay and OC content of the soils, the low BD could be a result of the dominance of micropores and few macropores. Macroporosity is naturally limited in heavy clay soils and affects the soil's ability to transmit water and air (Lin *et al.*, 2022); hence, there were visible mottles on the assessed soils.

Generally, soils with poor structure have low carbon, but, in this study, OC was relatively higher in all the tillage systems at both locations in the topsoil (0–30 cm). Johannes *et al.* (2017) discovered that visually assessed good structure quality soils have higher OC to clay ratios than those with poor structure quality. On average, the structure quality in the topsoil was moderately poor but the bulk density was optimally low. The negative relationship between bulk density and SubVESS scores in the same soil depth could be attributed to the increased clay content compared to that in the topsoil (Obour *et al.*, 2017). Imhoff *et al.* (2016) found that bulk density decreased with an increase in clay content, whereas the SubVESS scores indicated a poor structure even though the bulk density was low. The increased clay content in the subsoil reduces mostly the macroporosity, while the micropores are not severely affected. The significant positive relationship between VESS and SubVESS that was identified at Tshivhilwi supports the use of these two methods together, especially where VESS indicates poor soil structure. Although the VESS and/or SubVESS scores can be similar for the respective tillage systems, it is important to note that during the assessment, some key parameters such as mottling and strength varied when scoring at different sampling points. This means that even though the scores were similar (e.g., both Sq5 = poor) the degree of quality may differ. This was revealed by the low bulk density, which showed a significant difference between the tillage systems in the 30–60 cm soil depth where the SubVESS scores were all poor (i.e., Ssq = 5). It is acknowledged that laboratory analysis cannot be abandoned completely, but VESS can be used as a detector tool for early soil structural changes that can give a guide on the remediation.

4.5. Conclusion

VESS and SubVESS were able to effectively differentiate between the impacts of tillage systems on soil structural quality where NT had been practised for a long period (40+ years), while it could not do so where NT had been practised for a few years (8 years). The contrasting tillage intensity caused the differences in soil structure quality between the tillage systems and study sites. The soil structure quality was better under NT than CT at Tshivhilwi and Dzingahe. Opposing impacts of NT and CT on soil structure quality were identified between the study sites. The visual assessment outcome has shown to be site specific considering the combination of management practices and clay content. The VESS and SubVESS scores were related to quantitative parameters such as BD and we have corroborated their effectiveness for assessing soil structural quality. In addition, although the correlation was not significant the quantitative results supported the VESS and SubVESS outcome. If VESS indicates moderate to poor soil structure, further assessment in the soil depth below 30 cm with SubVESS is recommended. Since both tillage systems have shown temporal effects relating to the changes in soil structural quality, more research is suggested on the use of VESS for monitoring spatio-temporal changes of soil structural quality under different soil-crop management practices and soil textures.

CHAPTER 5

ASSESSMENT OF PORE CHARACTERISTICS, CO_2 EFFLUX AND UNSATURATED HYDRAULIC CONDUCTIVITY OF SOILS UNDER LONG TERM NO-TILLAGE SYSTEM

Abstract

Tillage systems generally have contrasting effects on soil structure which influences the porosity and consequently the transmission of gases and water. Soil pore structure has a direct impact on gas diffusion and hydraulic functions because it defines the transport and flow characteristics. The study was conducted at Tshivhilwi and Dzingahe in Thohoyandou, Vhembe District, Limpopo Province, South Africa. The soils under no-tillage (NT) and conventional tillage (CT), were assessed to check the pore characteristics, unsaturated hydraulic conductivity and CO_2 efflux; virgin fields (VGs) used as a control at each study site. Soil pore characteristics were determined in the 0–30 cm and 30–60 cm soil depths. CO_2 efflux was measured during dry and wet seasons. At Tshivhilwi; total porosity, pore connectivity and micropore volume were higher in NT in both soil depths. Macropore volume was highest in CT in the topsoil. At Dzingahe, estimated pore connectivity in NT and CT showed no difference in both soil depths. The estimated pore connectivity in the 0–30 cm depth was relatively higher in CT while in the 30–60 cm depth it was greater in NT. Virgin field had macropore volume which was seven and four times higher than in NT and CT, respectively. Soil CO_2 efflux was generally higher in wet season mainly due to high soil moisture content. CT had almost three times higher unsaturated hydraulic conductivity (K) than NT at Tshivhilwi but nearly equal at Dzingahe. Unsaturated hydraulic conductivity (K) was affected mostly by the soil surface conditions such as cracks. The volume of micropores increased with depth. Larger pores (>5 mm) that were mostly cracks constituted the greater percentage of the total pore volume. The findings of this study revealed significant improvements in total porosity, pore connectivity and micropore volume under NT after a short-term no-till practice however no differences were observed after long-term. Nevertheless, NT still showed better properties than CT. The impact of tillage system on hydraulic conductivity seemed to be overshadowed by the cracks observed on the surface due to the high clay content of the soil.

Key words: Tillage, porosity, infiltration, carbon dioxide

5.1. Introduction

Tillage systems generally have contrasting effects on soil structure which influences the porosity (Basset *et al.*, 2023; Lipiec *et al.*, 2006; Pan *et al.*, 2018; Panday and Nkongolo, 2021; Yudina and Kuzyakov, 2023) consequently the transmission of gases and water. In addition to soil structure, texture also has an impact on pore structure. However, the resulting pore sizes and shapes are temporary (Yudina and Kuzyakov, 2023) due to the changes of these soil properties especially structure. The impact of tillage systems on pore structure development and recovery of related hydraulic properties are vague regardless of substantial research over recent years (Wardak *et al.*, 2022). Soil pore structure has a direct impact on gas diffusion and hydraulic functions because it defines the transport and flow characteristics (Fomin *et al.*, 2023; Vogel and Roth, 2001). The soil pore structure have been widely characterized by the non-destructive X-ray microtomography (XµCT) technique (Beckers *et al.*, 2014; Bölscher *et al.*, 2021; Jarvis *et al.*, 2017; Munkholm *et al.*, 2012; Wardak *et al.*, 2022) to obtain microscale data.

There are still gaps in the understanding of the spatial and temporal variability of soil carbon dioxide efflux in response to hydrological changes (Riveros-Iregui *et al.*, 2008). Furthermore, the authors indicated that more focus is on the temporal than spatial component. Agricultural management practices such as tillage are known to have a significant impact on soil CO_2 emissions (Sainju *et al.*, 2021). Reduced tillage has been reported to decrease soil CO_2 emissions (Wang *et al.*, 2015), therefore, soils under no-tillage system are expected to have low CO_2 emission (Forte *et al.*, 2017). However, tillage effects on soil CO_2 emission are inconsistent and not well clarified (Gong *et al.*, 2021). Hence, it is important to study CO_2 dynamics under different tillage systems as it is one of the major contributors in global warming.

Hydraulic properties such as infiltration controls the soil's capacity to capture water (Blanco-Canqui and Ruis, 2018). Furthermore, infiltration controls crop water availability, leaching, ground water recharge and runoff (Franzluebbers, 2002; Pan *et al.*, 2018). Initial and final/terminal infiltration rates could be influenced by soil properties like total porosity, bulk density, organic matter and initial moisture content (Chyba *et al.*, 2017; Haghnazari *et al.*, 2015; Sun *et al.*, 2018). Basche and DeLonge (2019), suggested that management practices such as tillage also have an influence on soil infiltration rates. Tillage and compaction are the two key factors that affect the hydraulic characteristics of the soil (Haghnazari *et al.*, 2015). Generally, compaction will be shown by the high bulk density values, on the other hand, tillage should have a contrasting effect given that it keeps the soil structure in good condition.

The aim of the study was to assess pore characteristics, CO_2 diffusion and hydraulic conductivity of soils under long-term no-tillage and conventional tillage. The hypothesis was that tillage does not have an effect on soil pore characteristics, CO_2 diffusion and unsaturated hydraulic conductivity.

5.2. Materials and methods

5.2.1 Site description

Refer to 4.2.1. The study sites were characterised by the selected soil properties presented in Table 5.1.

Table 5.1: Selected soil properties at Tshivhilwi and Dzingahe.

Tillage system	BD (g/cm^3)	Clay (%)	Silt (%)	Sand (%)	BD (g/cm^3)	Clay (%)	Silt (%)	Sand (%)
	Tshivhilwi				Dzingahe			
	Soil depth (0–30 cm)							
NT	1.32a	37.60a	18.40a	44.00a	1.19a	26.53a	36.53a	36.93a
CT	1.37a	30.53a	23.47a	46.00a	1.22a	34.27a	35.07a	30.67a
VG	1.38a	34.67a	22.67a	42.67a	1.32b	32.00a	32.00a	36.00a
Soil depth (30–60 cm)								
NT	1.23a	41.47ab	13.20a	45.33a	1.20a	41.07a	30.80a	28.13a
CT	1.57b	34.93a	19.07a	46.00a	1.26a	48.93a	28.40a	22.67a
VG	1.39c	44.00b	14.27a	41.73a	1.44b	42.67a	27.33a	30.00a

The letters “a” and “b” indicate significant difference

5.2.2. Soil sampling

Soil sampling was carried out from the NT, CT and VG fields in Tshivhilwi and Dzingahe. The VG field was used as a control treatment at each location. Five sampling points were randomly selected in a portion (area = 1000 m^2) of each field per location considering the homogeneity of the soil. Five soil pits (1 m x 1 m x 0.7 m) were dug on the selected sampling points in each field per location. The sampling depths were 0 – 30 cm and 30 – 60 cm in a soil pit. Soil core samples were collected using PVC cylinders (diameter = 50 mm, height = 70 mm) on the walls of the soil profiles for X-ray micro-computed tomography analysis. The samples were allowed to dry at a room temperature before the analyses. A total of sixty soil samples were collected (30 topsoil and 30 subsoil) from both locations.

5.2.3. Soil pore characteristics by X-ray micro-computed tomography (XµCT)

Undisturbed core soil samples collected from the tillage systems were analysed with XµCT at the South African Nuclear Energy Corporation SOC Limited (Necsa), MIXRAD facility. Nikon XTH 225L micro-focus CT X-ray unit was used to scan the dry soil samples at 90keV/90µA. Total porosity and estimated pore connectivity were calculated from the obtained soil pore data.

$$Total\ porosity = \frac{pv_t}{sv} \times 100$$

$$Estimated\ pore\ connectivity = \frac{pv_l}{pv_t} \times 100$$

pv_t is the total volume of pores in the sample, sv is the sample volume, pv_l is the volume of the largest pore in the sample. The volume units were mm^3.

Macropores and micropores were categorised based on their diameters (0.1 – 5 mm and <0.01 mm respectively) (Weil and Brady, 2017). Macropores included biopores that were within the diameter range and excluded those that were greater than 5 mm. The soil cracks larger than 5 mm were also excluded. The total pore volume included all the pores in the samples even those that were larger than 5 mm. The volume percentages of macropores and micropores were calculated from the total pore volume of the sample.

$$macropore\ volume\% = \frac{v_l}{pv_t}$$

$$micropore\ volume\% = \frac{v_s}{pv_t}$$

v_l is the volume of macropores (0.1 – 5 mm) , v_s is the volume of micropores (<0.01 mm), pv_t is the total volume of pores in the sample (<0.01 mm, 0.1 – 5 mm, and >5 mm).

5.2.4. Unsaturated hydraulic conductivity

The mini-disk infiltrometer (METER Group, Inc., Pullman, USA) was used to measure the infiltration rate of the soil according to METER Group, Inc. manual. The suction rate of 2 cm was used for all the measurements. The recording of water level was adjusted to 5 minutes interval until it drops close to zero per measurement. Unsaturated hydraulic conductivity of the soils under NT, CT and VG was then calculated (Fatehnia *et al.*, 2014).

5.2.5. Soil carbon dioxide (CO_2) efflux

CO_2 was measured twice, first during the rainy season in March and second in the dry season in June using soil respiration model Vaisala CARBOCAP® Carbon Dioxide Probe GMP343 (Vaisala, Vantaa, Finland) (Munjonji *et al.*, 2020; Riveros-Iregui *et al.*, 2008). The PVC chambers were installed into the soil to a depth of 0.05 m leaving 0.1 m above the soil, ensuring a good seal between the chamber and the soil surface. They were left in the soil for some days to settle before taking the measurements. Carbon dioxide efflux readings were collected at 30 seconds intervals for 5 minutes per measurement. Soil CO_2 efflux was calculated by measuring the rate of increase in CO_2 concentration within the chamber. Soil temperature and water content were also recorded per measurement of CO_2. Soil temperature was recorded by the carbon dioxide probe GMP343. Soil water content was measured with a WET150 multiparameter soil sensor kit.

5.2.6. Data analysis

The collected data were subject to analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) at a 95% confidence interval ($p \leq 0.05$) to compare the parameters measured in the tillage systems per location using IBM SPSS statistics 29.0 statistical software. The unsaturated hydraulic conductivity in the same tillage systems was compared between locations and the CO_2 efflux in each tillage system was compared between seasons using MANOVA. Pearson correlation coefficient (r) was used to check the relationship between the parameters.

5.3. Results

5.3.1. Soil pore characteristics

The total porosity quantified by the X-ray computed tomography for samples collected at Tshihvilwi showed a significant difference between NT & CT ($p \leq 0.001$) and CT & VG ($p \leq 0.001$) in the 0–30 cm and 30–60 cm soil depths. No-tillage (27.75% and 33.65%) had a higher total porosity than CT (13.52% and 29.83%) and VG (27.21%

and 17.41) in both soil depth (Figure 5.1). The estimated pore connectivity was highest in NT (90.66% and 94.71%) in both soil depths, and differed significantly ($p = 0.026$) with VG in the 30–60 cm soil depth (Figure 5.2). Macropore volume was significantly different between NT and CT in the 0–30 cm and 30–60 cm soil depths ($p = 0.015$ and $p = 0.015$ respectively), then CT and VG ($p = 0.015$) in the 30–60 cm soil depth. Macropore volume was the highest in CT (7.57%), however, in the subsoil NT (6.59%) had almost double what was found in CT (3.42%) (Figure 5.4). Significant difference

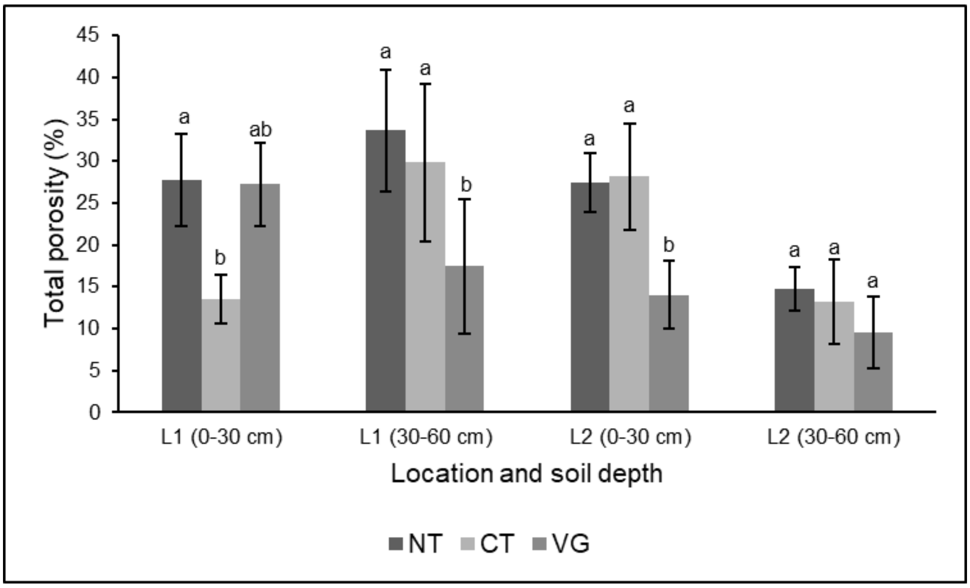


Figure 5.1: Total porosity comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2). Soil depth = 0–30 cm and 30–60 cm.

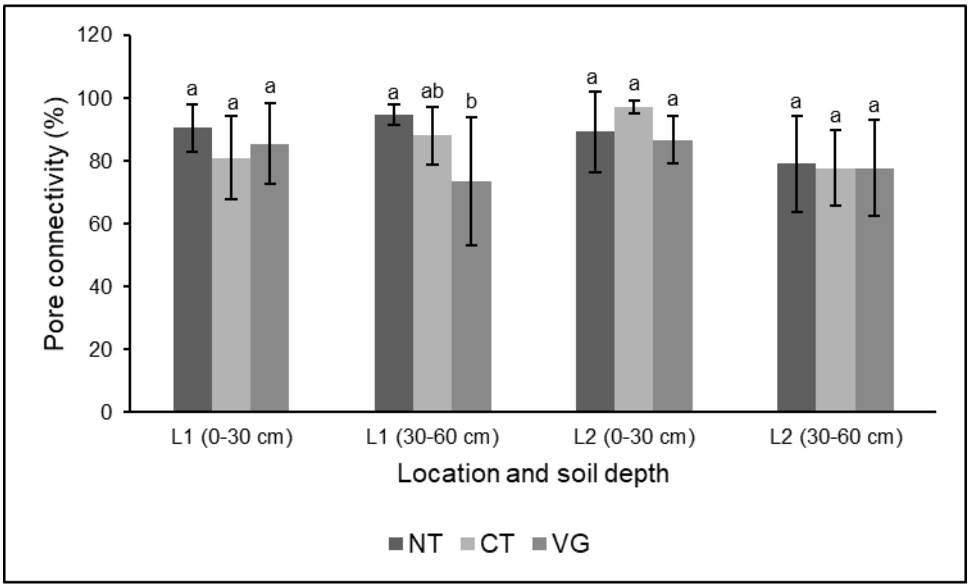


Figure 5.2: Estimated soil pore connectivity comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2). Soil depth = 0–30 cm and 30–60 cm.

in micropore volume between CT and VG in both soil depths ($p = \leq 0.001$ and $p = 0.016$); and between NT and CT in the 0–30 cm soil depth ($p = \leq 0.001$). No-tillage (1.60% and 1.86%) had a higher micropore volume than CT (0.83% and 1.53%) in the topsoil and subsoil (Figure 5.5). Some of the 3D images obtained after the analyses are displayed in Figure 5.3.

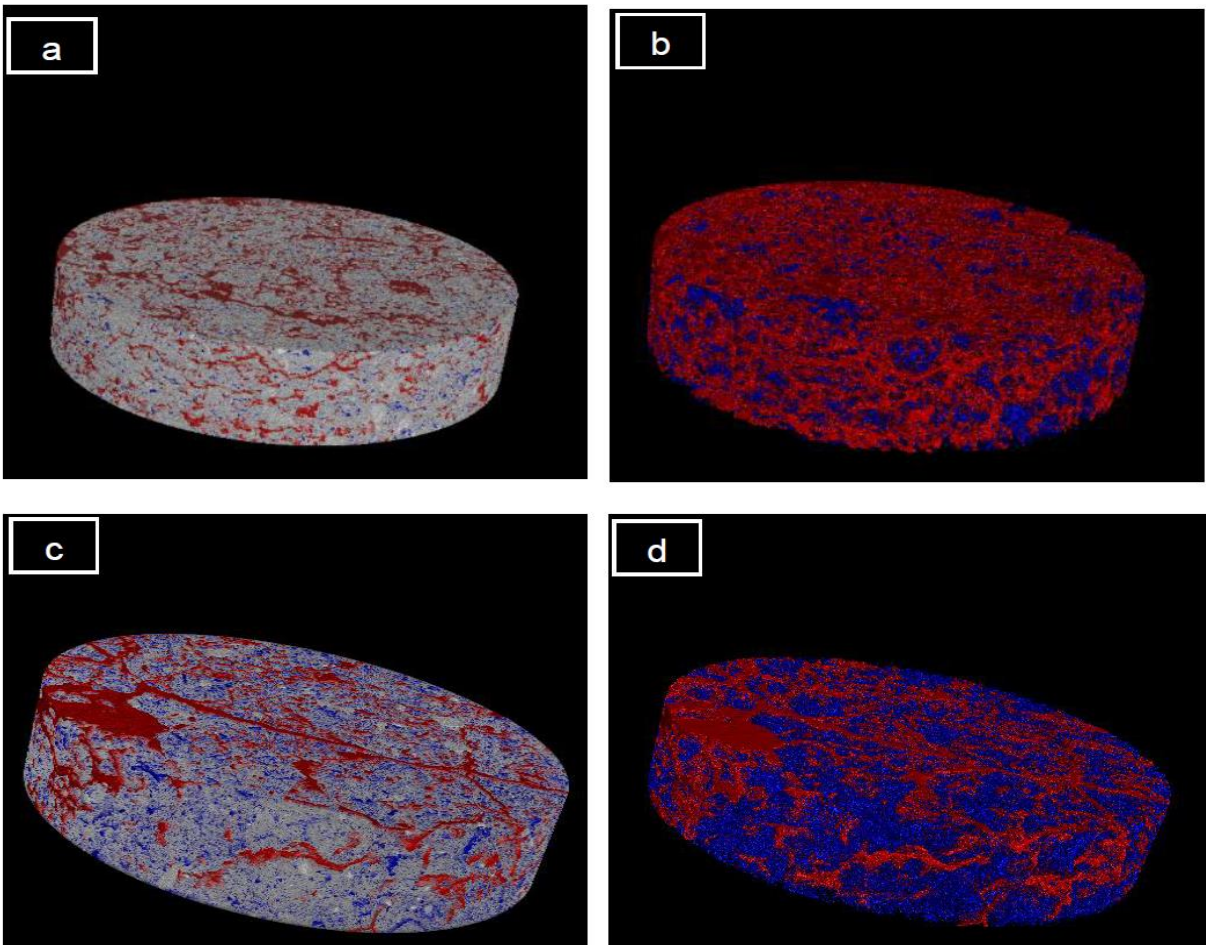


Figure 5.3: Example of X-ray computed tomography (CT) 3D images soil core sample collected from 0–30 cm and 30–60 cm soil depth (a & c respectively) under NT at Dzingahe. a & b are samples with pores; c & d shows pores only without soil. The blue colour shows the volume of the large pores (including cracks and biopores) and the red colour is the volume of the small pores.

The results at Dzingahe showed significant difference for soil total porosity between NT & VG ($p \leq 0.001$) and CT & VG ($p \leq 0.001$) in the 0–30 cm soil depth (Figure 5.1). Total porosity between NT & CT in the 30–60 cm soil depth and estimated pore connectivity in both soil depths between all tillage systems were not significantly different (Figure 5.1 and 5.2). Total porosity in NT (27.42% and 14.74%) and CT (28.13% and 13.16%) was almost equal in both soil depths (Figure 5.1). The estimated pore connectivity in the 0–30 cm soil depth was higher in CT (97.27%) than in NT

(89.33%) while in the 30–60 cm soil depth it was greater in NT (79.12%) than CT (77.84%) (Figure 5.2). The total porosity decreased with depth while the pores were more connected in the 0–30 cm soil depth than in 30–60 cm soil depth in all tillage systems. Macropores volume showed significant difference in the 0–30 cm soil depth between NT & VG ($p \leq 0.001$) and CT & VG ($p \leq 0.001$). Virgin field (16.17%) had macropore volume seven and four times what was found in NT (2.27%) and CT (3.78%) respectively. In the 30 – 60 cm soil, the volume of the macropores was highest in NT (15.89%) although it was not significant between the tillage systems (Figure 5.4). The volume of micopores also varied significantly between NT and VG ($p = 0.005$) in the 0–30 cm soil depth and CT & VG ($p = 0.008$ and $p = 0.020$) in both soil depths. Conventional tillage (0.39% and 4.25%) had more micropore volume than NT (0.22% and 3.02%) in the topsoil and subsoil (Figure 5.5).

There was no significant variation in total porosity and estimated pore connectivity identified in the same tillage system between the study sites. However, there was a significant differences of macropore and micropore volumes NT ($p = 0.045$), CT ($p = 0.033$) and VG ($p = 0.008$) between the study sites. Macropore volume was higher than macropore volume. The volume of micropores increased with depth, therefore, there were more micropores in the subsoil than topsoil. However, the cracks larger than 5 mm constituted highest percentage of the total pore volume. Hence, the volumes of macropores and micropores were lower (Data not shown).

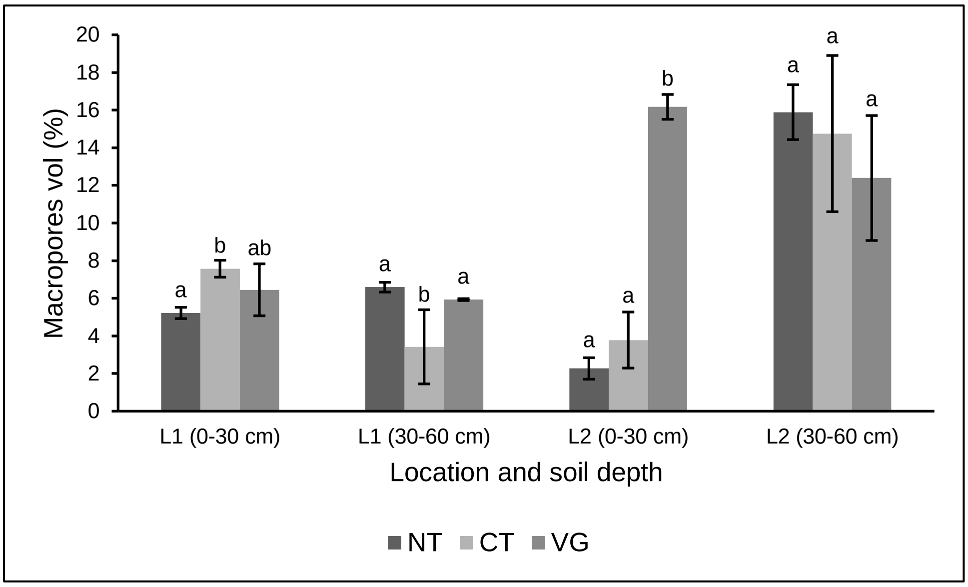


Figure 5.4: Macropore volume percentage comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2*)*. Soil depth = 0–30 cm and 30–60 cm.

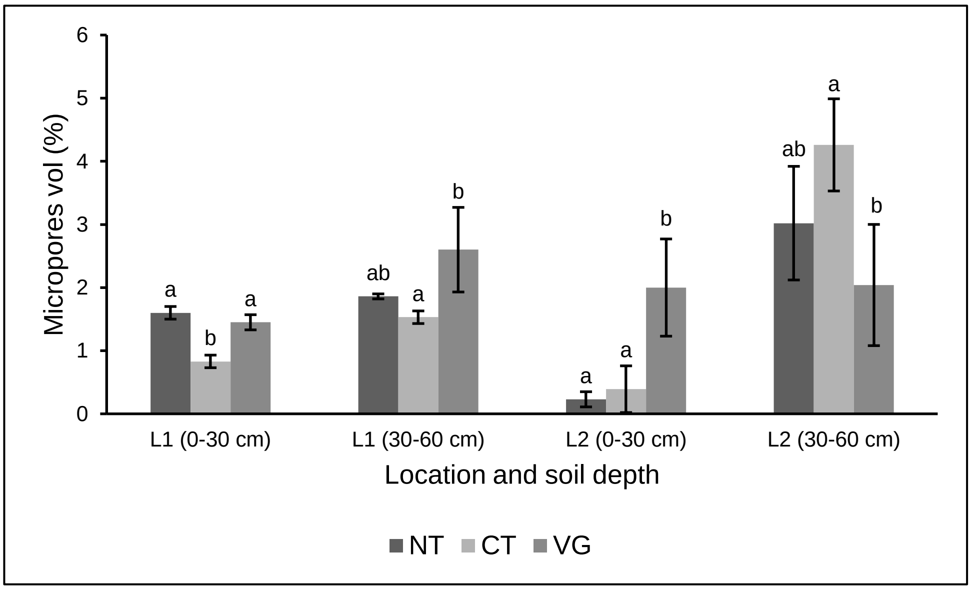


Figure 5.5: Micropore volume percentage comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2*)*. Soil depth = 0 – 30 cm and 30 – 60 cm.

5.3.2. Unsaturated soil hydraulic conductivity

The unsaturated hydraulic conductivity *(K)* results varied significantly between NT & CT ($p \leq 0.001$), CT & VG ($p \leq 0.001$) and NT & VG ($p = 0.026$) at Tshivhilwi. Conventional tillage had almost three times higher *K* (0.029 cm/min) than NT (0.010 cm/min), Virgin field was the lowest with *K* = 0.004 cm/min. However, at Dzingahe, the results indicated a significant difference between NT and VG only ($p = 0.045$). The *K*

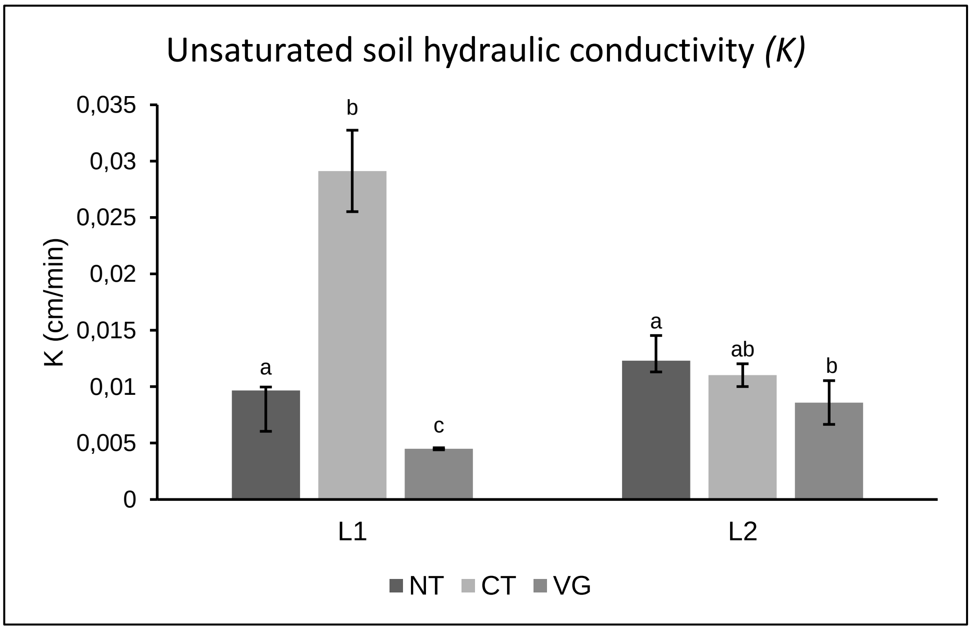


Figure 5.6: Unsaturated soil hydraulic conductivity (*K*) comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2).

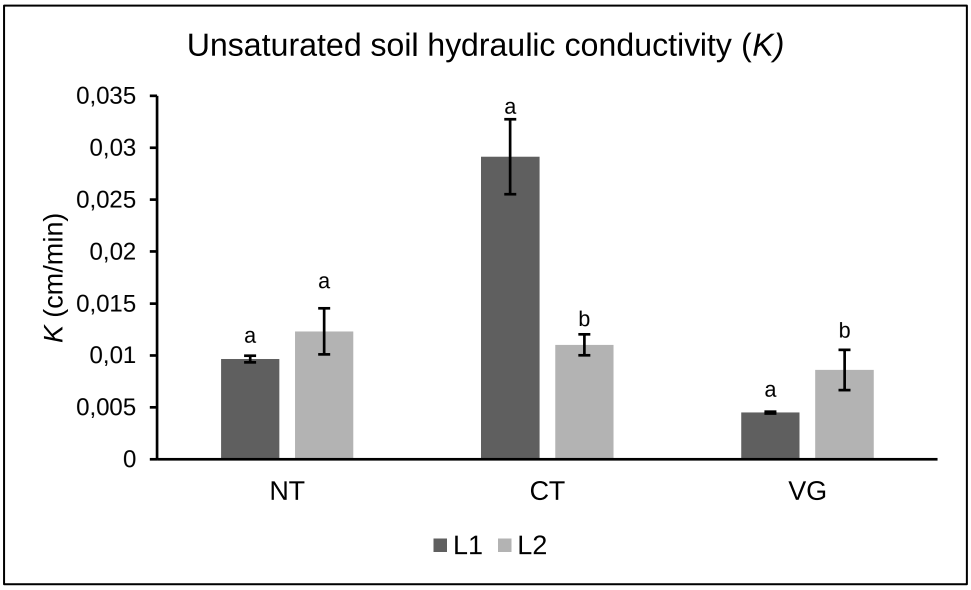


Figure 5.7: Comparing unsaturated soil hydraulic conductivity (*K*) under no-tillage (NT), conventional tillage (CT) and virgin field (VG) between Tshivhilwi (L1) and Dzingahe (L2).

in NT (0.012 cm/min) and CT (0.011 cm/min) were nearly equal, though it was the lowest in VG (0.009 cm/min) (Figure 5.6).

Significant unsaturated hydraulic conductivity (K) results were shown in CT ($p \leq 0.001$) and VG ($p = 0.029$) except in NT between Tshivhilwi and Dzingahe. However, K in NT (0,012 cm/min) was highest at Dzingahe while in CT (0,029 cm/min) it was highest at Tshivhilwi. The VG field had the highest K (0.009 cm/min) at Dzingahe (Figure 5.7). Soil moisture content (V%) was also measured, however, showed not to have exclusively influenced the K value trends (data not shown).

5.3.3. Soil carbon dioxide efflux

The results showed no significant differences in soil CO_2 efflux between NT, CT and VG during dry season at Tshivhilwi. Even though no significant difference were observed, the VG field had relatively the highest CO_2 efflux (4.95 mg/m^2/min) while CT (2.22 mg/m^2/min) had the lowest in dry season. During the wet season, NT & CT and CT & VG differed significantly ($p \leq 0.001$ and $p = 0.003$ respectively). The soil CO_2 efflux was 85% higher in CT (22.35 mg/m^2/min) compared to NT (3.40 mg/m^2/min) (Figure 5.8 and 5.9). At Dzingahe non-significant soil CO_2 efflux results were obtained between NT, CT and VG in both seasons. However, in the dry season, CT (5.55 mg/m^2/min) had the highest CO_2 efflux followed by NT (3.26 mg/m^2/min) and the lowest was VG with 4.38 mg/m^2/min. The same trend was identified in wet season where the soil CO_2 efflux values 10.47, 7.83 and 7.03 mg/m^2/min were recorded in CT, NT and VG respectively (Figure 8 and 9). Conventional tillage emerged to have the highest soil CO_2 efflux amongst the tillage systems at Tshivhilwi and Dzingahe in wet season.

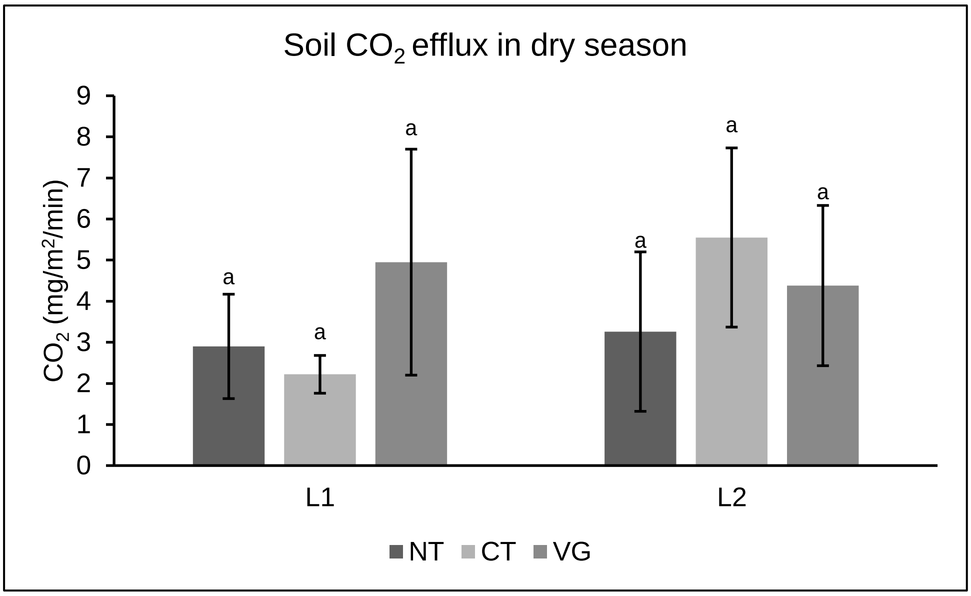


Figure 5.8: Soil CO_2 efflux comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi (L1) and Dzingahe (L2) during the dry season.

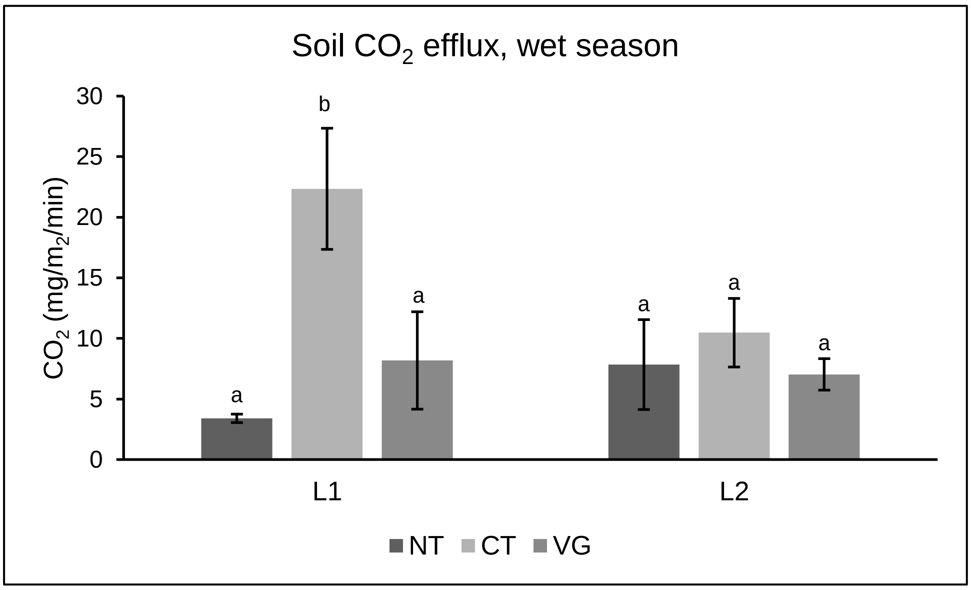


Figure 5.9: Soil CO_2 efflux comparison between no-tillage (NT), conventional tillage (CT) and virgin field (VG) at Tshivhilwi and Dzingahe during the wet season.

There was no significant difference in soil CO_2 efflux under NT between the dry and wet seasons at Tshivhilwi, it was highest (3.40 mg/m^2/min) during wet season and lowest in dry season (2.90 mg/m^2/min). However, significant (*p* = 0.010) results were found in Dzingahe where the soil CO_2 efflux during the wet season was double (9.74 mg/m^2/min) what was found in dry season (4.02 mg/m^2/min) (Figure 5.10). At Tshivhilwi the soil CO_2 efflux between the dry and wet season in CT was significant (*p* = 0.002). It was ten times higher during wet season (22.35 mg/m^2/min) than in dry season (2.22 mg/m^2/min). Similar trend in CT was identified at Dzingahe but the results were non-significant. The soil CO_2 efflux (10 mg/m^2/min) was higher in wet season than in dry season (5.55 mg/m^2/min) (Figure 5.10).

The soil CO2 efflux results in VG showed no significant difference between the seasons with the same trends as in NT and CT. Overall, soil CO2 efflux was highest during the wet season in all tillage systems. The soil moisture content was constantly higher in the wet season than in the dry season as it was expected at both study sites. So, the soil CO2 efflux increased with the soil moisture content, although, the temperature was inconsistent between dry and wet seasons (Table 5.2). However, contrasting effect of seasons on soil temperature, moisture content and CO2 efflux were identified in the study sites. At Tshivhilwi there was a significant difference (p = 0.010) between the seasons in NT only. Whereas at Dzingahe, significant difference was shown in CT (p = 0.009) and VG (p = 0.040).

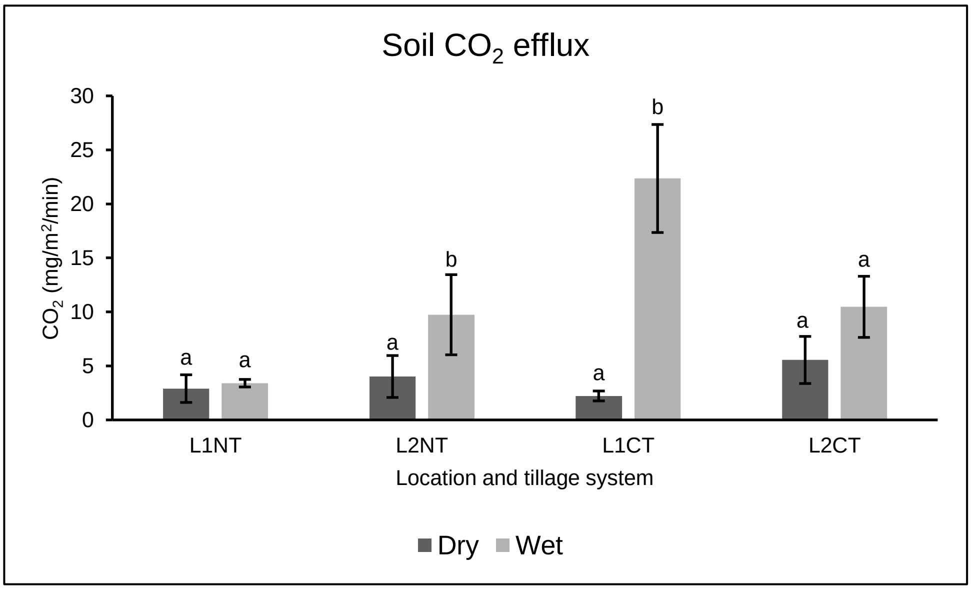


Figure 5.10: Soil CO_2 efflux comparison between the dry and wet seasons under no-tillage (NT) and conventional tillage (CT) at Tshivhilwi (L1) and Dzingahe (L2).

Table 5.2: Soil moisture and temperature measured with CO_2 efflux in the tillage systems during the dry and wet seasons.

	Tshivhilwi		**Dzingahe**	
	Temperature °C	**Moisture (V %)**	**Temperature °C**	**Moisture (V %)**
NT				
Dry	27.45a	16.53a	30.88a	13.53a
Wet	29.59a	34.67b	31.62a	33.43b
CT				
Dry	32.48a	14.33a	30.7a	10.93a
Wet	31.01b	42.63b	34.55b	34.8b
VG				
Dry	32.17a	21.30a	31.64a	16.47a
Wet	30.35b	40.27b	30.81a	39.53b

The letters “a” and “b” indicate significant difference

5.3.4. Relationship between the measured soil parameters.

The results at Tshivhilwi indicated that the soil CO_2 efflux in the dry season had a strong positive significant correlation with total pore volume (*r* = 0.916**), total porosity (*r* = 0.828**) and estimated pore connectivity (*r* = 0.720*), however a weak positive correlation was found with macropore (*r* = 0.042) and micropore (*r* = 0.359) volume. While on the other hand, it had a very weak negative correlation with moisture content (*r* = -0.110) and temperature (*r* = - 0.023) in the same season. During the wet season, a strong positive correlation was found between soil CO_2 efflux and temperature (*r* = 0.375), moisture (*r* = 0.127), estimated pore connectivity (*r* = 0.190) and macropore volume (*r* = 0.744*), however, soil CO_2 efflux correlated negatively with micropore volume (*r* = -0.671*), total pore volume (*r* = - 0.16) and total porosity (*r* = -0.448). Unsaturated hydraulic conductivity correlated negatively with total pore volume (*r* = -0.757*), total porosity (*r* = -0.798*), estimated pore connectivity (*r* = -0.436) and micropore volume (*r* = -0.870**). Total porosity and estimated pore connectivity had a moderate positive correlation (*r* = 0.527). Macropore and micropore volumes showed a negative correlation (r = -0.647).

The results at Dzingahe showed soil CO_2 efflux in dry season correlated negatively with soil moisture content (*r* = -0.253), temperate (*r* = -0.353), total pore volume (*r* = -

0.035) micropore volume (*r* = -0.099), whereas a very weak positive correlation was found with macropore volume (*r* = 0.077), total porosity (*r* = 0.064) and estimated pore connectivity (*r* = 0.09). However, in the wet season soil CO_2 efflux correlated positively with soil moisture content (*r* = 0.262), temperature (*r* = 0.570), total pore volume (*r* = 0.256), total porosity (*r* = 0.239) and estimated pore connectivity (*r* = 0.296). However, soil CO_2 efflux during the wet season correlated negatively with macropore (*r* = -0.234) and micropore (*r* = -0.085) volume. There was a significant negative correlation of estimated pore connectivity with macropore (*r* = -0.809**) and micropore (*r* = -0.771*) volume. *K* has shown a positive correlation with total pore volume (*r* = 0,510), total porosity (*r* = 0,640) and estimated pore connectivity (*r* = 0,600). But, *K showed* a significant negative correlation with macropore (*r* = -0.755*) and micropore (*r* = -0.838**) volume There was a strong significant positive correlation between total porosity and estimated pore connectivity (*r* = 0.867^{**}). Macropore and micropore volume showed a very strong significant positive correlation (*r* = 0.924**).

5.4. Discussion

The total porosity and estimated pore connectivity were generally higher in NT than CT, whereas macro- and micropore volumes were inconstantly lower and/or higher between the tillage systems. The operations in these tillage system have caused modification on soil properties (such as structure and bulk density) that may have altered the pore characteristics in the topsoil and subsoil. This was also found by Alletto *et al.* (2022) where soil properties including porosity varied between the fields under conventional and conservation agriculture (i.e. no-tillage). The two tillage systems are believed to have opposing effects on the soil structure which is a dynamic key factor that overtime may change the pore characteristics and water and air transmission. In addition, compaction is also a problem under these tillage systems, however, the soils were not compacted based on bulk density values (Table 5.1). Generally soils that are not compacted allow an adequate flow of water and air. Soil particle size distribution may have also played an important role in determining the pore characteristics.

At Tshihvilwi total porosity and pore connectivity increased with depth in NT and CT whereas a negligible decrease with depth was observed in VG. On the other hand, at Dzingahe total porosity and estimated pore connectivity decreased with depth in all tillage systems. Micropore volume increased with depth, although, the macropore volume was higher than micropore volume at both study sites and all tillage systems. The higher micropore volume could be due to the more clay content in the subsoil compared to the topsoil (Table 5.1). While the greater macropore volume could be attributed to the cracks. Furthermore, the cracks also contributed to the high pore connectivity. However, it is important to point out that the cracks are temporary because they usally close when the soil becomes wet. Total porosity and pore connectivity were greater in NT than CT, which was similar to the findings of Galdos *et al.* (2019). These differences could have attributed to the duration of the tillage systems as it was found by Cooper *et al.* (2021) and Blanco-Canqui and Ruis (2018). The duration of these tillage determines the degree of the changes in soil pore characteristics which depended on the level of compaction and condition of the soil structure. Furthermore, the varied percentages of the clay content and the presence of small stones (~ 5 mm) also resulted to the observed pore characteristics. The distribution of fine soil particles such as clay in the topsoil and subsoil could have contributed substantially to the reduced total porosity, pore connectivity, macropore and micropore volume through clogging (Alletto *et al.*, 2022). It is important to note that the pore size distribution and their volumes in the soil are key to total porosity and pore connectivity.

The alteration of the total porosity, pore size distribution and pore connectivity can affect the soil's ability to transmit gases and water from the surface, potentially through to the lower parts of the profile. Thus, the permeability of the soil depends on the pore size distribution and connectivity. This controls how water moves into and through the soil (Haruna *et al.*, 2018). However, the relationship between unsaturated hydraulic conductivity *(K)* with total porosity and estimated pore connectivity was inconsistent. At Tshivhilwi, a negative relationship with total porosity and estimated pore connectivity was observed while it was positive at Dzingahe. In addition, the unsaturated hydraulic conductivity was notably influenced by the initial soil moisture content (Bát'ková *et al.,* 2020) and soil surface conditions such as cracks. The intial infiltration was high due to the cracks because they allow a rapid water flow. On the other hand, the initial infiltration rate was high as the initial soil moisture content was low and there was more space for water to pass through. But, the infiltration rate decreased until it was constant as more water entered the soil maybe due to closed cracks or pores filled with water. Contrasting results were also recorded where CT had higher *K* than NT at Tshivhilwi, while at Dzingahe in NT it was higher than CT, this could be attributed the intensity of the tillage and cropping systems. At Tshivhilwi crop rotation in NT was practiced throughout the year while at Dzingahe only maize (mono-cropping) was grown during the rainy season. These practices influences the surface soil structural conditions that alter the pore characteristics, therefore, affecting the movement of water into the soil.

Carbon dioxide (CO_2) efflux from the soil is also dependent on the pore characteristics (Fomin *et al.*, 2023), although the moisture content and temperature regulates the the emission rates (Gong *et al.*, 2021; Hao *et al.*, 2023). There was a positive relationship of soil CO_2 efflux with total porosity and estimated pore connectivity though the strength varied in the two study sites. In the dry and wet seasons, CT had a higher soil CO_2 efflux than NT except at Tshivhilwi during dry season where it was higher in NT. The higher CO_2 efflux in CT during wet season could be attributed to the increased respiration due to rapid decomposition rate of the crop residues that are incorporated into the soil (Balesdent *et al.*, 2000; Maier *et al.*, 2020; La Scala *et al.*, 2006). Unlike under NT, most of the crop residues are left on the soil surface, therefore not exposed to intensive microbial decomposition. Kay and VandenBygaart (2002) highlighted that under NT the leaching and microbial redistribution of organic solutes are the primary transportation channel. The crop residues that remain on the soil surface under NT also helps to conserve soil moisture which could have resulted in the higher CO_2 efflux at Tshivhilwi in the dry season. The amount of soil moisture content played a major role in the CO_2 efflux and this was shown by the higher values during wet season than in dry season in all tillage systems. Moist soil conditions are favourable for microorganisms, so they are very active and decompose more organic material hence there was higher CO_2 during wet season. Yet, the release of CO_2 from the soil depends on pore connectivity and macro porosity. Soil temperature fluctuations could have also contributed because it was ± 30 °C in both seasons. Gong *et al.* (2021), La Scala *et al.* (2006) and Tang *et al.* (2003) also found that CO_2 efflux changes were dependent on soil temperature fluctuation and changes in water content. Nonetheless, the soil CO_2 efflux may vary according to climatic zones as the study was conducted in a subtropical region.

5.5. Conclusion

Contradictory results were obtained between the tillage systems at Tshivhilwi and Dzingahe which might be attributed to the inconsistencies in their execution and practices such as crop rotation and intercropping. However, NT was mostly better than CT. Furthermore, there were also differences in measured parameters that were identified in the same tillage systems between the study sites. The tillage systems shown to have modified the pore characteristics of the soil, which to some extend affected the hydraulic conductivity and CO_2 efflux. The volume of micropores increased with depth. Larger pores (>5 mm) that were mostly cracks accounted the highest percentage of the total pore volume. It was notable that soil moisture content affected the CO_2 efflux. This was shown by a higher CO_2 efflux during wet season than dry season in all tillage systems. The management of these tillage systems especially NT needs to be improved to maintain good soil structure, therefore favourable soil pore characteristics for adequate gas and fluid flow. More research is needed with higher temporal and spatial variability on the soil CO_2 efflux within the same and between season(s) in different tillage systems as it was discovered that soil moisture content and temperature fluctuations contributed considerably to the CO_2 emission.

CHAPTER 6

ASSESSING THE IMPACT OF NO-TILL DURATION ON SOIL AGGREGATE SIZE DISTRIBUTION, STABILITY AND AGGREGATE ASSOCIATED CARBON

Abstract

Soil aggregation is a complex process that results from the interaction between physical, chemical and biological properties. It results from the rearrangement, flocculation and cementation of primary soil particles by agents such as organic carbon, clay content and biota. Long-term of no-tillage can improve aggregation and their stability and organic carbon storage capacity than short-term no-tillage. The amount of carbon vary in different aggregate size fractions. This study assessed the impact of tillage system, soil depth and no-till duration on soil aggregate size distribution, stability and aggregate associated carbon. It was carried out in Tshivhilwi and Dzingahe, Thohoyandou, Vhembe district, Limpopo province, South Africa. The No-tillage fields in Tshivhilwi and Dzingahe were 8 years (short-term) and >40 years (long-term) respectively. Macro-aggregates constituted the largest proportion of aggregates with percentage contribution of > 60% during short-term and long-term. The mean weight diameter (MWD) only showed significant difference between NT and VG in the 30 – 60 cm soil depth after 8 years of NT. The MWD was higher in short-term NT than long-term NT. There was no significant difference in organic carbon in all aggregates size fractions between the tillage systems in both soil depths after 8 years. Organic carbon in all aggregate fractions between the tillage systems in the 0 – 30 cm soil depth was not significantly affected after more than 40 years. The percentage of large macro-aggregates and micro-aggregates was inconsistently and relatively lower across the tillage systems in the short- and long-term. MWD was higher in the 30 – 60 cm than 0 – 30 cm soil depth in NT and CT during both periods. Micro-aggregates contained greater OC than other fractions.

Key words: Tillage, soil depth, aggregates

6.1. Introduction

Soil aggregation is a complex process that results from the interaction between physical, chemical and biological properties (Totsche *et al.*, 2018). It results from the rearrangement, flocculation and cementation of primary soil particles (Mohanty *et al.*, 2012). Furthermore, it is determined by agents such as organic carbon, clay content and biota. Tillage, cropping systems, fertilisation among others also have impact on aggregation. Beillouin *et al.* (2023) stated that management practices such as no-tillage, crop diversification or rotation and crop residue retention contribute to soil organic carbon increase. Kumar *et al.* (2013) added that structure (i.e. aggregates) and organic matter are dynamic soil properties that are very sensitive to soil and crop management practices. Generally, no-tillage increases aggregate stability and soil organic matter content (Bai *et al.*, 2018).

Long-term no-tillage system can improve aggregation and their stability and organic carbon storage capacity than short-term no-tillage (Sekaran *et al.*, 2021). Furthermore, no-tillage perform better than conventional tillage on maintenance of soil structure and carbon storage. Conventional tillage destroys soil aggregates and this lead to the loss of carbon due to hastened oxidation of organic matter (Weidhuner *et al.*, 2021). On the other hand, no-tillage promote aggregation due to less mechanical disturbance of the soil which may also enhance carbon storage within the aggregates. Weidhuner *et al.* (2021) reported that no-tillage increased aggregate associated carbon of silty loam soil than conventional tillage practices. Topa *et al.* (2021) added that long-term no-tillage in a temperate climatic zone can increase aggregate stability because of the reduced disturbance and retention of crop residues on the soil surface as compared to conventional tillage. Fernández-Ugalde *et al.* (2009) also discovered a significant improvement of aggregate size distribution and stability after seven years of continuous no-tillage. Long-term no-tillage has been found to have a positive effect on the accumulation of organic carbon and aggregation more especially in the 0–10 cm soil depth compared to conventional tillage (Oliveira *et al.*, 2020) and this may also extend to the lower soil depths. The adoption of no-tillage results in increased aggregate stability along the soil profile compared to conventional tillage (Mondal and Chakraborty, 2022). However, the authors further indicated that long-term no-till can also have a positive impact on other parameter such as the aggregate stability. This was shown by the increase in mean weight diameter (MWD) in 0 – 10 cm soil depth for the years <10, 10–20 and >20, but the entire profile increase was only recorded for the duration of more than 20 years.

Soil organic matter contains approximately 55% organic carbon and 45% other essential elements (Kumar *et al.*, 2013). Jensen *et al.* (2019) added that soil organic carbon is the main component of soil organic matter and can serve as a proxy for soil structural stability. Soil organic carbon is the type carbon that is stored in the organic matter (Sekaran *et al.*, 2021). It is added to the soil through crop residue decomposition, microbes and root exudates. Organic matter contribute significantly to the formation soil aggregates and the carbon within them is protected against degradation (Das *et al.*, 2014). Soil organic carbon act as binding agent in aggregate formation (Bronick and Lal, 2005). Furthermore, the amount of carbon vary in different aggregate size fractions. High accumulation of soil organic carbon in the micro-aggregates results in the effective formation of macro-aggregates under no-tillage (Du *et al.*, 2013; Sekaran *et al.*, 2021; Six *et al.*, 2000). Rabot *et al.* (2018) added that primary soil particles (< 20 μm) are joint together into micro-aggregates (20–250 μm), which are then bound to form macro-aggregates (> 250 μm). On the other hand, the disintegration of macro-aggregates forms smaller aggregates (20–250 μm) that are much more stable (Boix-Fayos *et al.*, 2001). This may also lead to the loss of some of the soil organic carbon.

The main purpose of this study was to assess the impact of tillage system, soil depth and no-till duration on soil aggregate size distribution, stability and aggregate associated carbon. The following research questions were asked: i) What impact does tillage system have on the distribuition of aggregates, their stability and aggregate associated carbon?, ii) Does the duration of no-till practice have an influence on soil aggregate size distribution, stability and aggregate associated carbon? and iii) Does aggregate stability and aggregate associated carbon vary in diffrent soil depths in the same tillage system?

6.2. Materials and methods

6.2.1 Site description

Refer to 4.2.1. The study sites were characterised by the selected soil properties presented in Table 6.1.

Table 6.1: Soil bulk (BD) and clay percentage in the 0–30 cm and 30–60 cm soil depth in no-tillage (NT), conventional tillage (CT) and virgin field (VG) under short-term and long-term.

Tillage system	**Tshivhilwi**		**Dzingahe**	
	BD (g/cm^3)	**Clay (%)**	**BD (g/cm^3)**	**Clay (%)**

0–30 cm				
NT	1.32a	37.60a	1.19a	26.53a
CT	1.37a	30.53a	1.22a	34.27a
VG	1.38a	34.67a	1.32b	32.00a
30–60 cm				
NT	1.23a	41.47ab	1.20a	41.07a
CT	1.57b	34.93a	1.26a	48.93a
VG	1.39c	44.00b	1.44b	42.67a

The letters a, b and c indicate significant difference

6.2.2. Soil sampling

Soil sampling was carried out from the no-tillage (NT), conventional (CT) tillage and virgin (VG) fields in Tshivhilwi and Dzingahe. The virgin (VG) field was used as a control treatment at each location. Five sampling points were randomly selected in a portion (area = 1000 m^2) of each field per location considering the homogeneity of the soil. Five soil pits (1 m x 1 m x 0.7 m) were dug on the selected sampling points in each field per location. The sampling depths were 0–30 cm and 30–60 cm in a soil pit. The samples were allowed to dry at a room temperature before analyses. A total of sixty soil samples were collected (30 topsoil and 30 subsoil) from both locations.

6.2.3. Aggregate size distribution and stability determination

The aggregate size distribution was determined by placing a 100 g dry subsample on a stack of sieves (4, 2, 0.212 and 0.50 mm). Aggregates were separated by vibrations with a sieve shaker for 5 minutes. Each aggregate size fraction was weighed except aggregates greater than 4 mm which were discarded. Mean weight diameter was then calculated (Cooper *et al.*, 2021):

$$MWD = \sum_{i=1}^{n} x_i w_i$$

MWD = mean weight diameter
xi = mean diameter of each size fraction size (mm)
wi = proportion of total sample weight (g)
n = number of size fractions

Table 6.2: Aggregate size categories based on diameter.

Category	**Diameter (mm)**
Large macro-aggregates	>2 mm
Macro-aggregates	0.212–2 mm
Micro-aggregates	0.05–0.212 mm

6.2.4. Aggregate associated organic carbon analysis

Organic carbon in each aggregate size fraction was analysed using Walkley & Black method (Meersmans *et al.*, 2009)

6.2.5. Data analysis

The collected data were subject to analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) at a 95% confidence interval ($p \leq 0.05$) to compare the parameters measured in the tillage systems per location using IBM SPSS statistics 29.0 statistical software. Aggregate size fractions, mean weight diameter (MWD) and aggregate associated organic carbon between 0–30 cm and 30–60 cm soil depths in each tillage system and duration (8 years and 40 years) of NT were computed with MANOVA. Pearson correlation coefficient (r) was used to check the relationship between the parameters.

6.3. Results

6.3.1. Aggregate size distribution and mechanical stability

At the site where no-tillage was practiced for 8 years (short term), it was observed that NT had almost three times (30.45%) more larger aggregates (>2 mm) compared to in CT (11.75%) and twice those of VG (16.98%) in the 0 – 30 cm soil depth (Figure 6.1a). However, NT had a significant lower percentage of micro aggregates compared to CT ($p = 0.027$) but did not differ with the VG in the same depth. No significant differences were observed between the tillage systems for aggregates ranging between 0.212 to 2 mm. Macro-aggregates (0.212 – 2 mm) constituted the largest proportion of aggregates with percentage contribution of > 60% (Figure 6.1a & b).

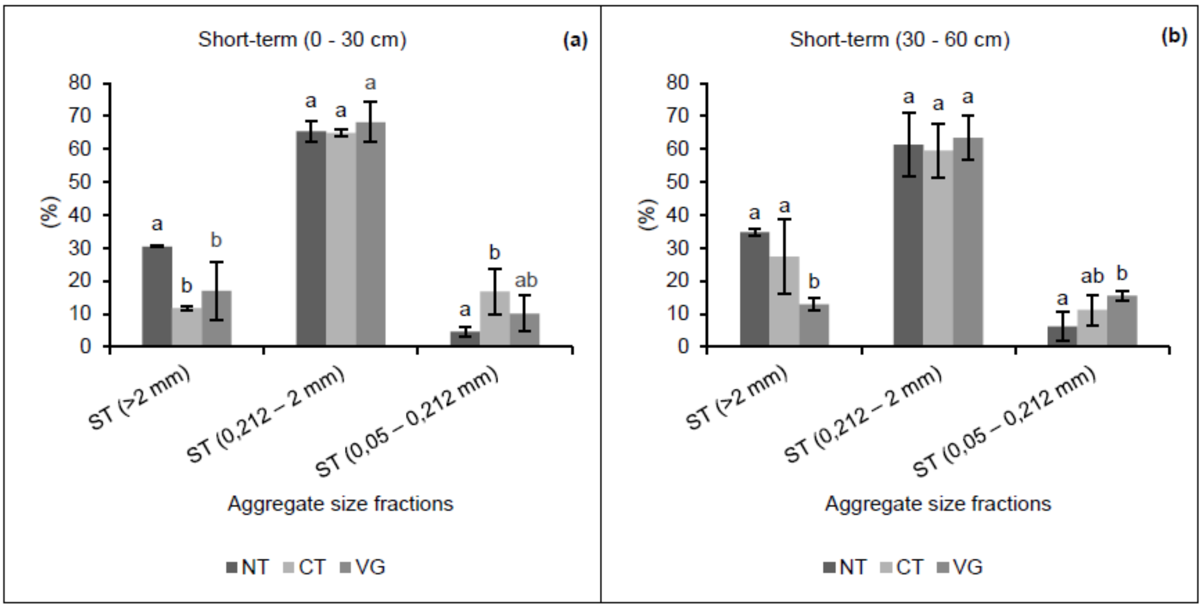


Figure 6.1 (a, b): Comparison of aggregate size fractions in the 0–30 cm and 30–60 cm soil depths between no-tillage (NT), conventional tillage (CT) and virgin field (VG) during 8 years (short-term: ST) tillage.

At the site where no-tillage was practiced for over 40 years (long-term), micro-aggregates showed a significant difference between NT & CT (*p* = 0.044) and CT & VG (*p* = 0.044) in the 0–30 cm soil depth (Figure 6.2a). Large macro-aggregates (>2 mm) were at least 2% higher in NT (18.67%) than CT (16.23%) in the 0–30 cm soil depth. Similar trend in the percentage of macro-aggregates (0.212 – 2 mm) was also found in the 0–30 cm soil depth in NT (62.72%) and CT (59.11%). However, micro-aggregates in the same depth were 5% higher in CT (23.19%) than NT (17.31%) and almost two times higher than VG (12.70%). In the 30–60 cm soil depth, large macro-aggregates in CT (23.95%) were 3% more than NT (20.28%), whereas macro-aggregates were just over 1% higher in NT (62.21%) than CT (60.33%). On the other hand there was a 1% difference of micro-aggregates between NT (15.82%) and CT (14.82%) (Figure 6.2b). Macro-aggregates constituted the largest proportion of aggregates with percentage contribution of > 60% (Figure 6.2a and b), which is similar to what was found in the short-term duration.

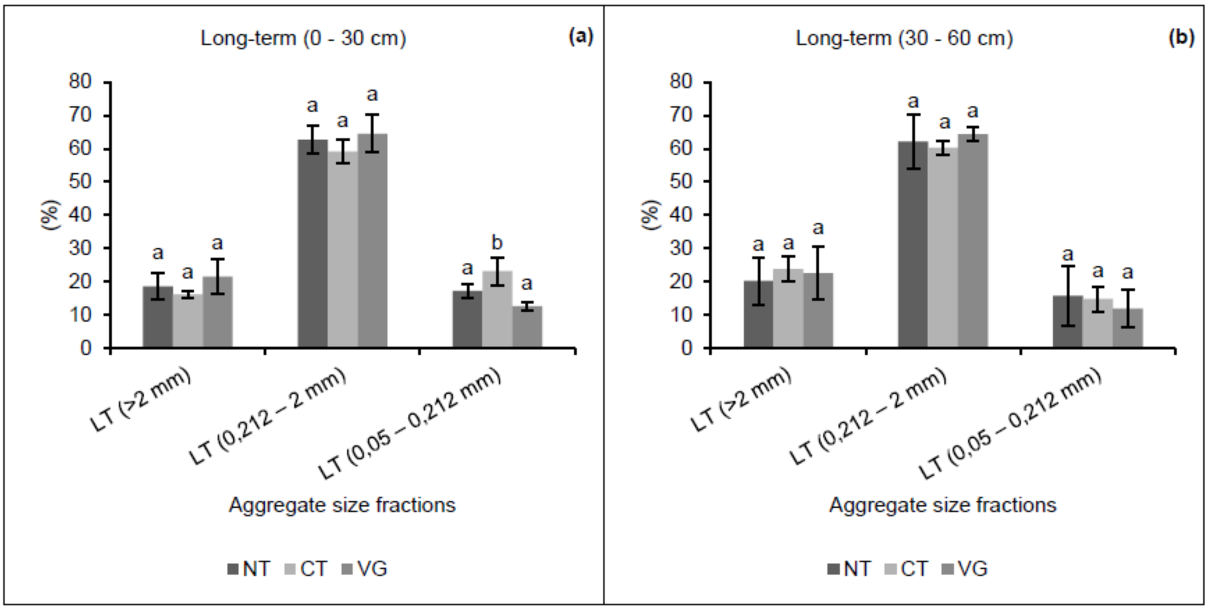


Figure 6.2 (a, b): Comparison of aggregate size fractions in the 0–30 cm and 30–60 cm soil depths between no-tillage (NT), conventional tillage (CT) and virgin field (VG) during >40 years (long-term: LT) tillage

The MWD only showed significant difference between NT and VG (*p* = 0.027) in the 30–60 cm soil depth after 8 years of NT (Figure 6.3). Even though no differences were observed in the top soil, it was relatively higher in NT with 1.25 mm compared to CT (1.06mm) and VG (1.22 mm). In the subsoil, a similar trend was also observed where MWD was higher in NT compared to the other tillage systems. After more than 40 years of no-till practice, the MWD was non-significant between all tillage systems except between CT and VG (*p* = 0.007) in the 0–30 cm soil depth (Figure 6.3). It was higher in VG (1.18 mm) than in NT (1.11 mm) and CT (1.17 mm) in the topsoil and subsoil. MWD was also higher in VG (1.18 mm) than CT (1.17 mm) and NT (1.11 mm) in the 30–60 cm soil depth.

The aggregate size distribution and MWD were also compared between short-term (8 years) and long-term (>40 years) NT only (data not shown). Large macro-aggregates and micro-aggregates in the topsoil were significantly (p = 0.006 and p = 0.001 respectively) affected by the duration of NT. Large macro-aggregates in the subsoil also showed significant difference (p = 0.026). The percentage of micro-aggregates was almost 4 and 3 times greater in the topsoil and subsoil respectively in long-term NT (17.31 and 15.82%) than short-term NT (4.57 and 6.27%). Whereas, the MWD was higher in short-term NT (1.25 and 1.31 mm) than long-term NT (1.09 and 1.00 mm) in both soil depths.

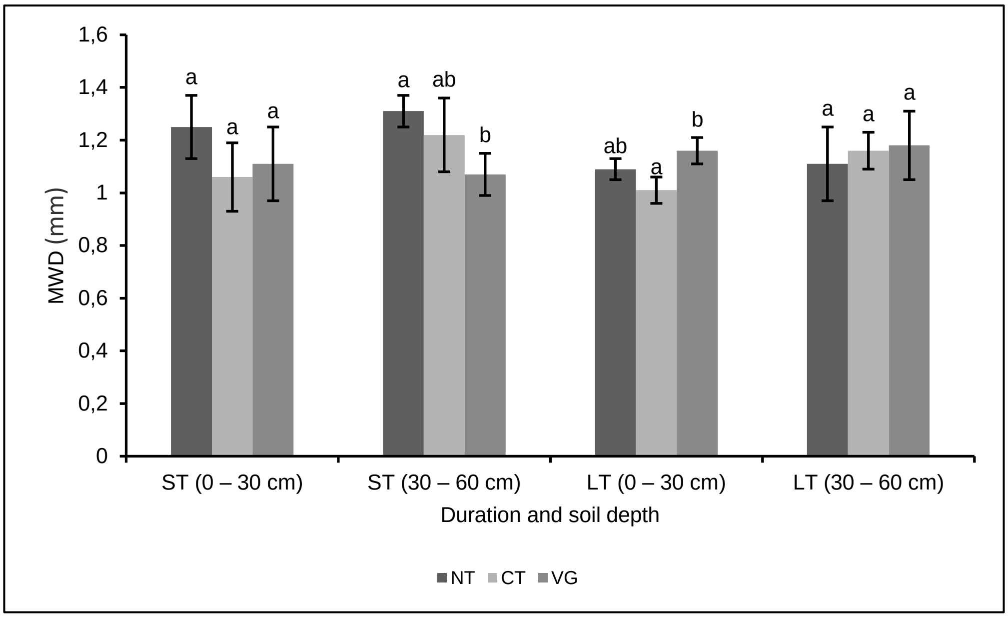


Figure 6.3: Comparison of mean weight diameter (MWD) in the 0–30 cm and 30–60 cm soil depths between no-tillage (NT), conventional tillage (CT) and virgin field (VG) during 8 years (short-term: ST)- and >40 years (long-term: LT) tillage.

The aggregate size distribution and MWD in the 0–30 cm and 30–60 cm soil depth were compared in each tillage system (data not shown). Overall, soil depth did not significantly affect the aggregate size distribution and MWD in each tillage system during short-term and long-term. However, the large macro-aggregates (p = 0.024) and MWD (p = 0.034) differed significantly in CT under long term. Subsoil indicated a more stable structural stability than topsoil in NT and CT.

6.3.2. Aggregate associated organic carbon (OC)

There was no significant difference in OC in all aggregates size fractions between the tillage systems in both soil depths after 8 years (short term) (Figure 6.4a and b). However, macro-aggregates (0.212 – 2 mm) and micro-aggregates (0.05 – 0.212 mm) had relatively more OC in the NT (1.30% and 1.58% respectively) in the 0–30 cm soil depth. In the 30–60 cm depth, NT also showed relatively higher OC in all the aggregate size fractions. The OC under NT in the large macro-aggregates, macro-aggregates and micro-aggregates was 0.70%, 0.92% and 0.98% compared 0.60%, 0.53% and 0.72% in CT and 0.57%, 0.65% and 0.71% in VG respectively.

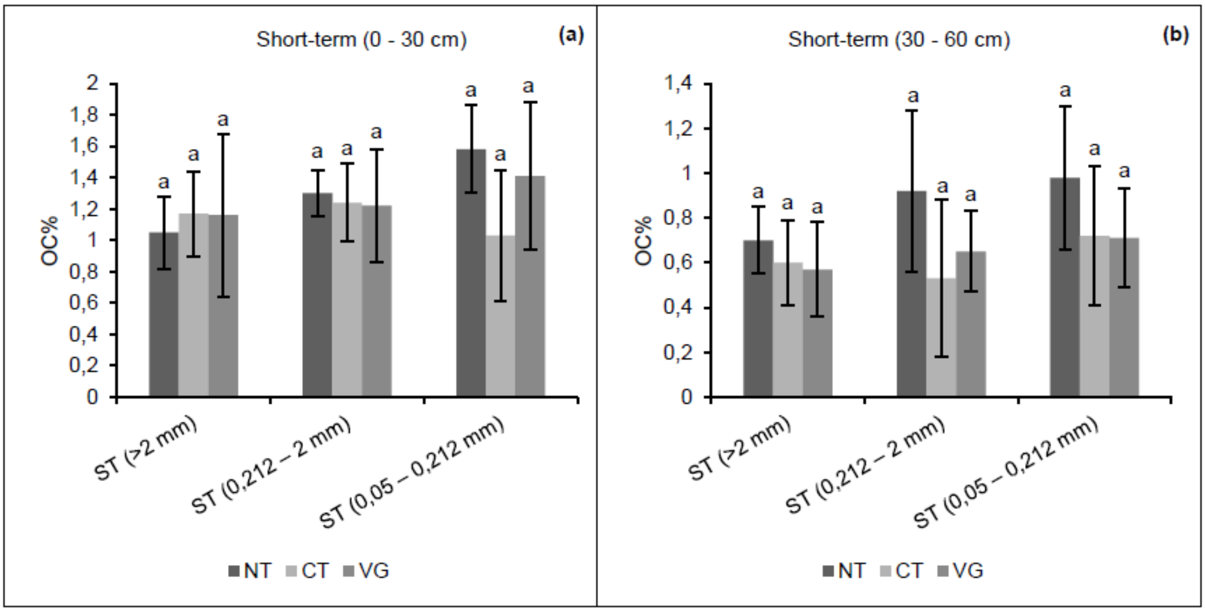


Figure 6.4 (a, b): Comparison of organic carbon (OC) in different aggregate size fractions in the 0–30 cm and 30–60 cm soil depths between no-tillage (NT), conventional tillage (CT) and virgin field (VG) afters 8 years (short-term: ST)).

Organic carbon in all aggregate fractions between the tillage systems in the 0–30 cm soil depth was not significantly affected after more than 40 years (long term) (Figure 6.5a). Even though no significant differences were observed in the topsoil, large macro-aggregates and macro-aggregates in NT showed higher OC (1.80% and 1.93%) than CT (1.58% and 1.80%) and VG (1.34% and 1.44%) while micro-aggregates in CT (2.28%) had more OC than NT (1.92%) and VG (1.80%) in the 30–60 cm soil depth. Organic carbon in both large macro-aggregates and macro-aggregates was significantly higher in CT compared to VG in the 30–60 cm depth (Figure 6.5b).

The OC in large macro-aggregates and macro-aggregates was significantly affected by the duration of NT in both soil depths. All aggregate fractions contained more OC in the long term (>40 years) NT than short term (8 years) NT. It was ranging from 0.72% to 1.93% in the long-term and 0.70 to 1.58% in the short-term. Overall, the results showed that the OC in all these aggregate size fractions was not significantly

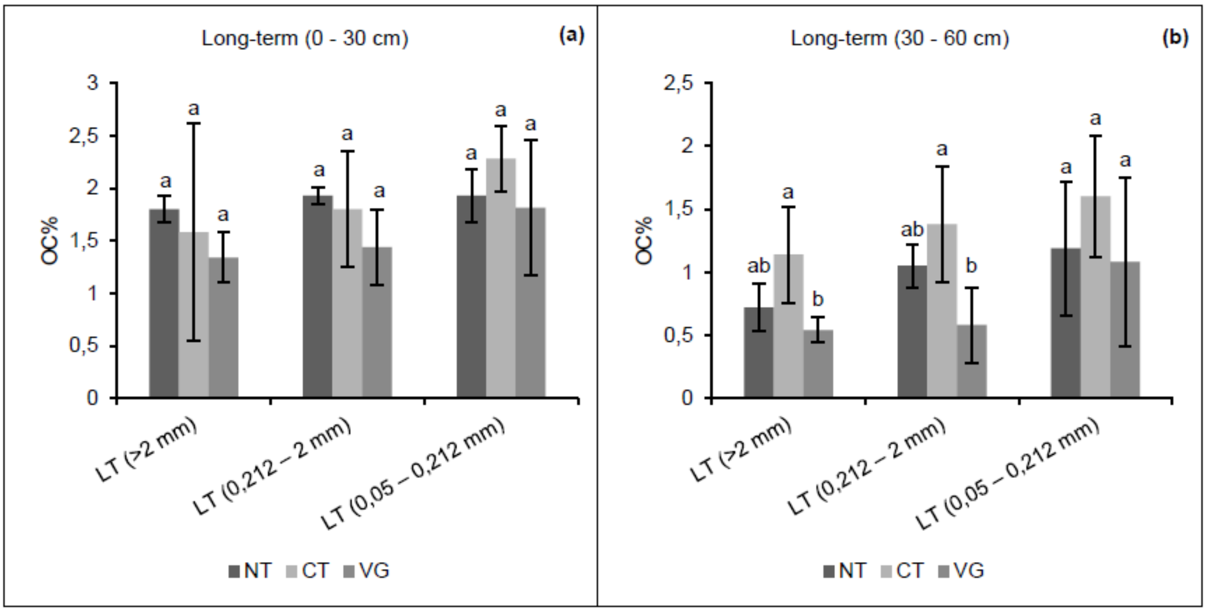


Figure 6.5 (a, b): Comparison of organic carbon (OC) in different aggregate size fractions in the 0–30 cm and 30–60 cm soil depths between no-tillage (NT), conventional tillage (CT) and virgin field (VG) afters >40 years (long-term: LT).

affected by soil depth. The aggregate associated OC was however more in the topsoil than subsoil (Data not shown).

6.3.3. Correlation between the measured soil parameters

The MWD in both soil depths in the short-term showed a negative relationship with macro-aggregates (r = -0,232 and r = -0.531) and micro-aggregates (r = -0.940** and r = -0.864**), but it was significant and strong positive with large macro-aggregates (r = 0.973** and r = 0.943**). There was a weak positive correlation between clay content and MWD (r = 0.328) in the 0–30 cm soil depth, and a very weak negative correlation (r = -0.135) in the 30–60 cm soil depth. The correlation between bulk density and MWD was negative (r = -0.432 and r = -0.352) in both soil depths. The aggregate OC of all fractions in both soil depths correlated positively with MWD except large macro-aggregates in the 0–30 cm depth.

In the long-term tillage (>40 years), MWD in both soil depths correlated positively with large macro-aggregates (r = 0.830** and r = 0.912**) and macro-aggregates (r = 0.339 and r = 0,156), and negatively with micro-aggregates (r = -0.918** and r = -0.940**). Bulk density also correlated positively with MWD (r = 0.458 and r = 0.318) in both soil depths. Clay content in the 0 – 30 cm showed a very weak positive correlation with MWD (r = 0.080), however, in the 30 – 60 cm it was positive (r = 0.393). The aggregate

OC of all fractions in both soil depths correlated negatively with MWD which is in contrast to the results in the short-term.

6.4. Discussion

The results showed a high percentage of macro-aggregates in both soil depths and all tillage systems. They accounted more percentage than other aggregate size fractions, which was similar to what was found by Six *et al.* (2000). However, there were noticeable differences in aggregate size distribution between the tillage systems. It was evident that tillage systems influenced the distribution soil aggregates. The conspicuous dominance of macro-aggregates fraction in all tillage systems and depths could be due to the high clay content of the soil. Clay particles act as cementing agents during aggregation and soils that have a high proportion of clay tend to form relatively larger aggregates (Bronick and Lal, 2005; Rabot *et al.*, 2018). Conventional tillage (CT) had the highest percentage micro-aggregates than NT in the topsoil (0–30 cm) under both short- and long-term no-till system. However, in the subsoil (30–60 cm) micro-aggregates were higher in CT in the short-term and in NT in the long term. This could be attributed to the intensity and duration of these tillage systems at both study sites. Conventional tillage has a destructive tendency towards soil structural stability which mostly mechanically pulverise aggregates in the soil, whereas, NT is known to promote aggregation (Weidhuner *et al.*, 2021). The duration of either tillage system contributes largely to the resultant aggregate size distribution as the changes occur over time. It is also believed that the degree of the impact of the tillage systems on aggregate size distribution and stability could have been modified by additional management practices such as crop rotation, mono-cropping, inter-cropping and residue management. In the study conducted by Zhou *et al.* (2020), it was clear that cropping systems affected the soil aggregate stability and organic carbon storage. These cropping systems contributed to the amount of organic matter added to the soil as crop residues after harvest, therefore the organic carbon content stored in the soil. On the other hand the tillage systems influenced the amount that is retained. Soils under NT have shown more organic carbon storage than those under CT.

The overall stability of the aggregates of the soils in all tillage systems as shown by the MWD was medium (Zeng *et al.*, 2018). The stability of individual aggregate fractions contributes to the overall structural stability of the soil. The soil aggregates were more stable in NT except in the long-term where they were more stable in CT in the 30 – 60 cm soil depth and this concur with the findings of Mondal and Chakraborty (2022). Du *et al.* (2013) and Fernández-Ugalde *et al.* (2009) reported a greater MWD in the topsoil (0 – 30 cm) in NT than CT which is in accordance to what was found in this study. The higher aggregate stability in NT could be attributed to the less soil disturbance that mostly helps preserve the structure as compared to CT. The key factors on the effect of tillage on aggregate stability is the frequency, intensity and period of the tillage (Mondal and Chakraborty, 2022; Oliveira *et al.*, 2020). This was indicated by the differences in number of years and cropping systems under NT. The relationship between bulk density and MWD between the tillage periods was not consistent. It was negative in 8 years and positive after more than 40 years. Regardless of this contrasting relationship, the low bulk densities generally showed that the soils were not compacted and MWD was moderate. Clay percentage showed a positive relationship with MWD except in short-term in the 30 – 60 cm where it was negative. Moreover, the higher clay content in the subsoil may have influenced the higher MWD than in the topsoil. Zeng *et al.* (2018) also found a significant increase in MWD with clay content. Oliveira *et al.* (2020) also reported conflicting results where MWD decreased with depth in the NT. The low bulk density and high clay content supported the fractionation and moderate stability of the aggregates.

Organic matter together with clay content are among binding agents that contributes to the formation of soil aggregates (Ball *et al.*, 2005; Mohanty *et al.*, 2012). However, the activities in NT and CT manipulated the aggregation process where in some parts there were signs (i.e. surface crust) of destroyed aggregates. However, some aggregates of different sizes were still intact and stable. Micro-aggregates across the tillage systems had the highest organic carbon than other aggregate size fractions in both soil depth except in short term where macro-aggregates had greater organic carbon in CT. Boix-Fayos *et al.* (2001) and Yudina and Kuzyakov (2023) indicated micro-aggregates protects most of the carbon in the soil which supports the findings of this study. The findings are however contradictory to the findings of Zhou *et al.* (2020) who discovered small macro-aggregates (0.25 – 2 mm) to be the fraction with higher soil organic carbon. The OC content of micro-aggregates in both soil depths showed a contrasting trend between the tillage periods where in the short-term it was highest in NT while in the long-term it was highest in CT. However, NT showed to be better than CT in aggregate associated organic carbon in the topsoil which could have been due to the less mechanical alteration of the soil aggregates. Weidhuner *et al.* (2021) supported this by indicating that the disturbance of aggregates in CT create suitable soil conditions for organic carbon loss. Breaking macro-aggregates into micro-aggregates increases the surface area for organic carbon microbial oxidation (Acar *et al.*, 2018). Therefore, this will possibly lead to rapid OC loss. The impact of these tillage system on the aggregates contribute to the amount of organic carbon stored and/or lost in the soil.

6.5. Conclusion

The soil in short-term (8 years) NT had more structural stability than long-term (>40 years) NT as it was shown by the MWD which was medium. However, MWD was higher in the 30–60 cm than 0–30 cm soil depth in NT and CT during both periods. Macro-aggregates constituted the highest percentage compared to other fractions. The percentage of large macro-aggregates and micro-aggregates was inconsistently and relatively lower across the tillage systems in the short- and long-term. Micro-aggregates contained greater OC than other fractions. All aggregate fractions contained more OC in the 0–30 cm than 30–60 cm soil depth. Further research is recommended to investigate the effect of CT and NT duration on aggregate size distribution, stability and capacity to store carbon under different soil textures.

CHAPTER 7

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The review indicated that visual evaluation of soil structure (VESS) method is effective for assessing structure as one of the principal soil quality indicators. The review identified studies where VESS successfully differentiated the structural quality of the clayey soils as influenced by management practices. VESS findings showed that NT had a better soil structure quality than CT, although contrasting effects these tillage systems were recorded. It is generally known that laboratory and some field quantitative measurements are expensive but VESS provides a cheaper and simple alternative method that can be used in soil quality assessment and monitoring. One of the advantages of this method is that non-experts can easily execute it with minimal training which can be one – two days. The adoption of the VESS method in South Africa and other countries where it is not commonly used will enable marginal and small holder farmers with limited resources to include soil structure assessment in the routine soil characterisation.

The duration of the no-tillage system influenced soil structure and related properties. Furthermore, tillage operation intensity, crop rotation and residue management may have played a major in the soil physical conditions. No-tillage showed better soil pore characteristics than CT. But, this does not always translate to a better air and water transmission in NT. There were visible cracks on the soil due to the activity of clay which further influenced hydraulic and gas diffusion properties of the soil. The unsaturated hydraulic conductivity between the study sites revealed contrasting trends where at Tshivhilwi it was higher in CT then at Dzingahe was higher in NT. Similarly, more CO_2 was emitted in CT at Tshivhilwi and in NT at Dzingahe. Furthermore, CO_2 emission was high during wet season than dry season. However, CT had a higher emission rate in both seasons. This could indicate that the disruption of soil structure and incorporation of residues in CT exacerbate global warming which also aggravate climate change due to the amount of CO_2 released to the atmosphere. The mean weight diameter (MWD) in NT indicated a moderate structural stability in the short-term (8 years) and long-term (>40 years) NT, however, it was higher in the short term. Surprisingly, MWD was higher in the subsoil than topsoil in NT and CT for both the short-term and long-term no-till duration. Macro-aggregates dominated in both the short-term and long-term no-till systems. Micro-aggregates had higher organic carbon storage capacity compared to other fractions. The capacity of aggregates to protect carbon prevents the loss to the atmosphere. Monitoring, maintenance and conservation of soil quality is important to keep the soils productive in order to achieve food security for the growing population in the developing countries like South Africa.

The recommendations from this study are that:

- More research on local soils is required using VESS in routine soil characterisation to check the physical quality and to emphasis its effectiveness. Most farmers especially those with limited resources neglect soil physical parameters when they characterise the soil for production. Farmers and land users need to adopt this method so that they can be able to assess and monitor the changes in soil structure as it serves as an effective alternative to quantitative methods.
- The findings of this study indicated that the changes on soil structure and related parameters under NT and CT on the measured results occur overtime and are site specific. So, there is need to consider spatio-temporal heterogeneity in soil structure studies because different soils respond different to these tillage systems. Furthermore, rapid and cheap method(s) are required to monitor those changes for conservation of soil quality and sustainable production in agricultural lands.
- Further research should be conducted on the optimum soil moisture content for executing VESS in different soil textures as it involves fractionation of the sample and it may for the same soils depending on moisture.
- Specific remediation guidelines for different soil textures should be included on the VESS method based on the structural quality score.
- NT should be combined with cropping systems like diversified crop rotation and intercropping to maintain good soil structural quality. This can further help to reduce CO_2 emissions from the soil to the atmosphere.
- Research is also needed on the recovery rate of damaged soil structure when converting from CT to NT and VESS can be used as a monitoring tool.

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LIST OF APPENDICES

Appendix 4.1: Analysis of variance (ANOVA) for VESS (Sq scores) between the tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Sq (0 – 30 cm)	Between Groups	0.936	2	0.468	1.106	0.362
	Within Groups	5.076	12	.423		
	Total	6.012	14			

Appendix 4.2: Analysis of variance (ANOVA) for SubVESS (Ssq scores) between the tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Ssq (30 – 60 cm)	Between Groups	0.000	2	0.000		
	Within Groups	0.000	12	0.000		
	Total	0.000	14			

Appendix 4.3: Analysis of variance (ANOVA) for VESS (Sq scores) between the tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Sq (0 – 30 cm)	Between Groups	4.379	2	2.190	4.906	0.028
	Within Groups	5.355	12	0.446		
	Total	9.734	14			

Appendix 4.4: Analysis of variance (ANOVA) for SubVESS (Ssq scores) between the tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Ssq (30 – 60 cm)	Between Groups	0.933	2	0.467	1.167	0.344
	Within Groups	4.800	12	0.400		
	Total	5.733	14			

Appendix 4.5: Analysis of variance (ANOVA) for bulk density (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
BD (g/cm^3) (0 – 30 cm)	Between Groups	0.010	2	0.005	0.701	0.516
	Within Groups	0.083	12	0.007		
	Total	0.092	14			

Appendix 4.6: Analysis of variance (ANOVA) for bulk density (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
BD (g/cm^3) (30 – 60 cm)	Between Groups	0.286	2	0.143	28.620	<0.001
	Within Groups	0.060	12	0.005		
	Total	0.346	14			

Appendix 4.7: Analysis of variance (ANOVA) for porosity (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
%P (0 – 30 cm)	Between Groups	10.807	2	5.403	0.303	0.744
	Within Groups	214.109	12	17.842		
	Total	224.916	14			

Appendix 4.8: Analysis of variance (ANOVA) for porosity (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
%P (30 – 60 cm)	Between Groups	340.077	2	170.039	9.703	0.003
	Within Groups	210.299	12	17.525		
	Total	550.376	14			

Appendix 4.9: Analysis of variance (ANOVA) for organic carbon (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
OC% (0 – 30 cm)	Between Groups	0.246	2	0.123	1.433	0.277
	Within Groups	1.029	12	0.086		
	Total	1.275	14			

Appendix 4.10: Analysis of variance (ANOVA) for organic carbon (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
OC % (30 – 60 cm)	Between Groups	0.324	2	0.162	0.935	0.420
	Within Groups	2.077	12	0.173		
	Total	2.401	14			

Appendix 4.11: Analysis of variance (ANOVA) for bulk density (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
BD (g/cm^3) (0 – 30 cm)	Between Groups	0.046	2	0.023	4.318	0.039
	Within Groups	0.064	12	0.005		
	Total	.109	14			

Appendix 4.12: Analysis of variance (ANOVA) for bulk density (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
BD (g/cm^3) (30 – 60 cm)	Between Groups	0.158	2	0.079	35.804	<0.001
	Within Groups	0.026	12	0.002		
	Total	0.184	14			

Appendix 4.13: Analysis of variance (ANOVA) for porosity (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
%P (0 – 30 cm)	Between Groups	62.714	2	31.357	4.160	0.042
	Within Groups	90.459	12	7.538		
	Total	153.173	14			

Appendix 4.14: Analysis of variance (ANOVA) for porosity (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
%P (30 – 60 cm)	Between Groups	112.925	2	56.462	3.753	0.054
	Within Groups	180.549	12	15.046		
	Total	293.474	14			

Appendix 4.15: Analysis of variance (ANOVA) for organic carbon (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
OC% (0 – 30 cm)	Between Groups	0.704	2	0.352	2.443	0.129
	Within Groups	1.729	12	0.144		
	Total	2.433	14			

Appendix 4.16: Analysis of variance (ANOVA) for organic carbon (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
OC % (30 – 60 cm)	Between Groups	0.749	2	0.375	3.363	0.069
	Within Groups	1.337	12	0.111		
	Total	2.087	14			

Appendix 4.17: Multivariate analysis of variance (MANOVA) for measured parameters in NT between Tshivhilwi and Dzingahe

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
NT Location	BD (g/cm^3) (0 – 30 cm)	0.044	1	0.044	5.918	0.041	0.425
	BD (g/cm^3) (30 – 60 cm)	0.003	1	0.003	1.940	0.201	0.195
	%P (0 – 30 cm)	116.417	1	116.417	6.281	0.037	0.440
	%P (30 – 60 cm)	2.134	1	2.134	.182	0.681	0.022
	OC % (0 – 30 cm)	0.824	1	0.824	23.568	0.001	0.747
	OC % (30 – 60 cm)	0.036	1	0.036	.304	0.597	0.037
	Sq (0 – 30 cm)	4.096	1	4.096	29.277	<0.001	0.785
	SSq (30 – 60 cm)	3.600	1	3.600	10.286	0.012	0.563

Appendix 5.1: Analysis of variance (ANOVA) for estimated pore connectivity (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
%P cnct (0 – 30 cm)	Between Groups	230.388	2	115.194	.878	
	Within Groups	1574.741	12	131.228		
	Total	1805.129	14			

Appendix 5.2: Analysis of variance (ANOVA) for estimated pore connectivity (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
%P cnct (30 – 60 cm)	Between Groups	1153.222	2	576.611	3.386	0.068
	Within Groups	2043.557	12	170.296		
	Total	3196.779	14			

Appendix 5.3: Analysis of variance (ANOVA) for macropore volume (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Macropore V% (0 – 30 cm)	Between Groups	8.291	2	4.146	5.671	0.041
	Within Groups	4.386	6	0.731		
	Total	12.677	8			

Appendix 5.4: Analysis of variance (ANOVA) for macropore volume (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Macropore V% (30 – 60 cm)	Between Groups	16.753	2	8.376	6.377	0.033
	Within Groups	7.881	6	1.313		
	Total	24.634	8			

Appendix 5.5: Analysis of variance (ANOVA) for micropore volume (0 – 30 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Micropore V% (0 – 30 cm)	Between Groups	0.995	2	0.498	41.379	<0.001
	Within Groups	0.072	6	0.012		
	Total	1.067	8			

Appendix 5.6: Analysis of variance (ANOVA) for micropore volume (30 – 60 cm) between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Micropore V% (30 – 60 cm)	Between Groups	1.786	2	0.893	5.771	0.040
	Within Groups	0.928	6	0.155		
	Total	2.714	8			

Appendix 5.7: Analysis of variance (ANOVA) for CO_2 efflux in dry season between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
CO_2. Dry (mg/m^2/min)	Between Groups	12.119	2	6.059	1.931	0.225
	Within Groups	18.827	6	3.138		
	Total	30.946	8			

Appendix 5.8: Analysis of variance (ANOVA) for CO_2 efflux in wet season between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
CO_2.Wet (mg/m^2/min)	Between Groups	582.877	2	291.439	21.204	0.002
	Within Groups	82.466	6	13.744		
	Total	665.343	8			

Appendix 5.9: Analysis of variance (ANOVA) for unsaturated hydraulic conductivity between tillage systems at Tshivhilwi

		Sum of Squares	df	Mean Square	F	Sig.
Unsaturated hydraulic conductivity. *K* (cm/min)	Between Groups	0.001	2	0.001	109.632	<0.001
	Within Groups	0.000	6	0.000		
	Total	0.001	8			

Appendix 5.10: Analysis of variance (ANOVA) for estimated pore connectivity (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
%P cnct (0 – 30 cm)	Between Groups	299.935	2	149.968	1.965	0.183
	Within Groups	915.833	12	76.319		
	Total	1215.768	14			

Appendix 5.11: Analysis of variance (ANOVA) for estimated pore connectivity (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
%P cnct (30 – 60 cm)	Between Groups	5.973	2	2.987	0.015	0.985
	Within Groups	2428.438	12	202.370		
	Total	2434.411	14			

Appendix 5.12: Analysis of variance (ANOVA) for macropore volume (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Macropore V% (0 – 30 cm)	Between Groups		2	174.469	176.274	<0.001
	Within Groups	5.939	6	.990		
	Total	354.876	8			

Appendix 5.13: Analysis of variance (ANOVA) for macropore volume (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Macropore V% (30 – 60 cm)	Between Groups	19.166	2	9.583	0.945	0.440
	Within Groups	60.839	6	10.140		
	Total	80.005	8			

Appendix 5.14: Analysis of variance (ANOVA) for micropore volume (0 – 30 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Micropore V% (0 – 30 cm)	Between Groups	5.755	2	2.878	11.557	0.009
	Within Groups	1.494	6	.249		
	Total	7.249	8			

Appendix 5.15: Analysis of variance (ANOVA) for micropore volume (30 – 60 cm) between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Micropore V% (30 – 60 cm)	Between Groups	7.392	2	3.696	4.917	0.054
	Within Groups	4.510	6	0.752		
	Total	11.902	8			

Appendix 5.16: Analysis of variance (ANOVA) for CO_2 efflux in dry season between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
CO_2. Dry (mg/m^2/min)	Between Groups	7.894	2	3.947	0.963	0.434
	Within Groups	24.590	6	4.098		
	Total	32.484	8			

Appendix 5.17: Analysis of variance (ANOVA) for CO_2 efflux in wet season between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
CO_2.2 (mg/m^2/min)	Between Groups	19.436	2	9.718	1.244	0.353
	Within Groups	46.882	6	7.814		
	Total	66.318	8			

Appendix 5.18: Analysis of variance (ANOVA) for unsaturated hydraulic conductivity between tillage systems at Dzingahe

		Sum of Squares	df	Mean Square	F	Sig.
Hydraulic conductivity. *K* (cm/min)	Between Groups	0.000	2	0.000	3.296	0.108
	Within Groups	0.000	6	0.000		
	Total	0.000	8			

Appendix 5.19: Multivariate analysis of variance (ANOVA) for CO_2 efflux in NT between dry and wet seasons at Tshivhilwi

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L1_NT Season	CO_2 (mg/m^2/min)	0.079	1	0.079	1.294	0.319	0.244
	T (°C)	6.851	1	6.851	1.325	0.314	0.249
	Moisture (V%)	493.227	1	493.227	21.792	0.010	0.845

Appendix 5.20: Multivariate analysis of variance (ANOVA) for CO_2 efflux CT between dry and wet seasons at Tshivhilwi

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L1_CT Season	CO_2 (mg/m^2/min)	608.246	1	608.246	48.344	0.002	0.924
	T (°C)	3.235	1	3.235	10.434	0.032	0.723
	Moisture (V%)	1201.335	1	1201.335	39.377	0.003	0.908

Appendix 5.21: Multivariate analysis of variance (ANOVA) for CO_2 efflux in NT between dry and wet seasons at Dzingahe

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L2_NT Season	CO_2 (mg/m^2/min)	49.137	1	49.137	19.752	0.011	0.832
	T (°C)	0.824	1	.824	2.539	0.186	0.388
	Moisture (V%)	594.015	1	594.015	12.465	0.024	0.757

Appendix 5.22: Multivariate analysis of variance (ANOVA) for CO_2 efflux in CT between dry and wet seasons at Dzingahe

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L2_CT Season	CO_2 ($mg/m^2/min$)	7.397	1	7.397	9.421	0.075	0.588
	T (°C)	22.199	1	22.199	617.990	<0.001	0.994
	Moisture (V%)	854.427	1	854.427	53.246	0.002	0.930

Appendix 5.23: Multivariate analysis of variance (ANOVA) for the measured parameters in NT between Tshivhilwi and Dzingahe

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
NT_Location	% Tot P (0 – 30 cm)	0.276	1	0.276	0.013	0.913	0.002
	% Tot P (30 – 60 cm)	894.159	1	894.159	29.766	<0.001	0.788
	%P cnct (0 – 30 cm)	4.382	1	4.382	0.039	0.849	0.005
	%P cnct (30 – 60 cm)	607.620	1	607.620	5.049	0.055	0.387
	Macro (0 – 30 cm)	13.009	1	13.009	62.776	0.001	0.940
	Macro (30 – 60 cm)	129.801	1	129.801	118.545	<0.001	0.967
	Micro (0 – 30 cm)	2.812	1	2.812	228.608	<0.001	0.983
	Micro (30 – 60 cm)	2.030	1	2.030	5.035	0.088	0.557

Appendix 5.24: Multivariate analysis of variance (ANOVA) for the measured parameters in CT between Tshivhilwi and Dzingahe

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
CT_Location	% Tot P (0 – 30 cm)	533.192	1	533.192	22.108	0.002	0.734
	% Tot P (30 – 60 cm)	694.556	1	694.556	12.227	0.008	0.604
	%P cnct (0 – 30 cm)	656.424	1	656.424	7.360	0.027	0.479
	%P cnct (30 – 60 cm)	265.946	1	265.946	2.372	0.162	0.229
	Macro (0 – 30 cm)	21.499	1	21.499	17.826	0.013	0.817
	Macro (30 – 60 cm)	192.474	1	192.474	18.232	0.013	0.820
	Micro (0 – 30 cm)	.294	1	.294	3.893	0.120	0.493
	Micro (30 – 60 cm)	11.119	1	11.119	40.814	0.003	0.911

Appendix 6.1: Analysis of variance (ANOVA) for large macro-aggregates (0 – 30 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
<2 mm (0 – 30 cm)	Between Groups	558,484	2	279,242	10,711	0.010
	Within Groups	156,419	6	26,070		
	Total	714,902	8			

Appendix 6.2: Analysis of variance (ANOVA) for macro-aggregates (0 – 30 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.212-2 mm (0 – 30 cm)	Between Groups	18.904	2	9.452	0.586	0.585
	Within Groups	96.725	6	16.121		
	Total	115.629	8			

Appendix 6.3: Analysis of variance (ANOVA) for micro-aggregates (0 – 30 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm (0 – 30 cm)	Between Groups	222,529	2	111,264	4,223	0.072
	Within Groups	158,068	6	26,345		
	Total	380,596	8			

Appendix 6.4: Analysis of variance (ANOVA) for MWD (0 – 30 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
MWD-mm (0 – 30 cm)	Between Groups	0.061	2	0.031	1.711	0.258
	Within Groups	0.107	6	0.018		
	Total	0.168	8			

Appendix 6.5: Analysis of variance (ANOVA) for large macro-aggregates (30 – 60 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
>2 mm (30 – 60 cm)	Between Groups	739,314	2	369,657	8,066	0.020
	Within Groups	274,977	6	45,830		
	Total	739,314	2	369,657	8,066	

Appendix 6.6: Analysis of variance (ANOVA) for macro-aggregates (30 – 60 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.212-2 mm (30 – 60 cm)	Between Groups	22.799	2	11.400	0.167	0.850
	Within Groups	409.567	6	68.261		
	Total	432.367	8			

Appendix 6.7: Analysis of variance (ANOVA) for micro-aggregates (30 – 60 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm (30 – 60 cm)	Between Groups	129.255	2	64.627	4.681	0.060
	Within Groups	82.845	6	13.808		
	Total	212.100	8			

Appendix 6.8: Analysis of variance (ANOVA) for MWD (30 – 60 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
MWD-mm (30 – 60 cm)	Between Groups	0.088	2	0.044	4.345	0.068
	Within Groups	0.061	6	0.010		
	Total	0.149	8			

Appendix 6.9: Analysis of variance (ANOVA) for large macro-aggregates (0 – 30 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
<2 mm (0 – 30 cm)	Between Groups	43.375	2	21.688	1.488	0.299
	Within Groups	87.428	6	14.571		
	Total	130.803	8			

Appendix 6.10: Analysis of variance (ANOVA) for macro-aggregates (0 – 30 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.212-2 mm (0 – 30 cm)	Between Groups	45.468	2	22.734	1.103	0.391
	Within Groups	123.621	6	20.604		
	Total	169.090	8			

Appendix 6.11: Analysis of variance (ANOVA) for micro-aggregates (0 – 30 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm (0 – 30 cm)	Between Groups	165.766	2	82.883	10.327	0.011
	Within Groups	48.156	6	8.026		
	Total	213.922	8			

Appendix 6.12: Analysis of variance (ANOVA) for MWD (0 – 30 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
MWD-mm (0 – 30 cm)	Between Groups	0.035	2	0.018	7.857	0.021
	Within Groups	0.013	6	0.002		
	Total	0.049	8			

Appendix 6.13: Analysis of variance (ANOVA) for large macro-aggregates (30 – 60 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
<2 mm (30 – 60 cm)	Between Groups	20.767	2	10.384	0.243	0.791
	Within Groups	256.068	6	42.678		
	Total	276.835	8			

Appendix 6.14: Analysis of variance (ANOVA) for macro-aggregates (30 – 60 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.212-2 mm (30 – 60 cm)	Between Groups	24.565	2	12.282	0.496	0.632
	Within Groups	148.497	6	24.749		
	Total	173.062	8			

Appendix 6.15: Analysis of variance (ANOVA) for micro-aggregates (30 – 60 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm (30 – 60 cm)	Between Groups	23.933	2	11.966	0.290	0.758
	Within Groups	247.695	6	41.282		
	Total	271.627	8			

Appendix 6.16: Analysis of variance (ANOVA) for MWD (30 – 60 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
MWD-mm (30 – 60 cm)	Between Groups	0.007	2	0.004	0.249	0.787
	Within Groups	0.086	6	0.014		
	Total	0.093	8			

Appendix 6.17: Analysis of variance (ANOVA) for micro-aggregates OC (0 – 30 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm_OC% (0 – 30 cm)	Between Groups	0.467	2	0.234	1.463	0.304
	Within Groups	0.958	6	0.160		
	Total	1.425	8			

Appendix 6.18: Analysis of variance (ANOVA) for micro-aggregates OC (30 – 60 cm) between tillage systems in the short-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm_ OC% (30 – 60 cm)	Between Groups	0.139	2	0.070	0.832	0.480
	Within Groups	0.503	6	0.084		
	Total	0.642	8			

Appendix 6.19: Analysis of variance (ANOVA) for micro-aggregates OC (0 – 30 cm) between tillage systems in long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm_OC% (0 – 30 cm)	Between Groups	0.362	2	0.181	0.947	0.439
	Within Groups	1.146	6	0.191		
	Total	1.508	8			

Appendix 6.20: Analysis of variance (ANOVA) for micro-aggregates OC (30 – 60 cm) between tillage systems in the long-term

		Sum of Squares	df	Mean Square	F	Sig.
0.05-0.212 mm_OC% (30 – 60 cm)	Between Groups	0.455	2	0.227	0.712	0.528
	Within Groups	1.915	6	0.319		
	Total	2.370	8			

Appendix 6.21: Multivariate analysis of variance (MANOVA) for the measured parameters between 0 – 30 cm and 30 – 60 cm soil depths in NT in the short-term

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L1_NT depth	<2 mm	39.219	1	39.219	0.749	0.436	0.158
	0.212-2 mm	25.958	1	25.958	0.512	0.514	0.114
	0.05-0.212 mm	0.944	1	0.944	0.045	0.843	0.011
	MWD-mm	0.005	1	0.005	0.487	0.524	0.108
	<2 mm_ OC%	0.186	1	0.186	4.905	0.091	0.551
	0.212-2 mm_ OC%	0.222	1	0.222	2.864	0.166	0.417
	0.05-0.212 mm_OC%	0.538	1	0.538	5.801	0.074	0.592

Appendix 6.22: Multivariate analysis of variance (MANOVA) for the measured parameters between 0 – 30 cm and 30 – 60 cm soil depths in CT in the short-term

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
CT depth	<2 mm	202.537	1	202.537	2.229	0.210	0.358
	0.212-2 mm	43.578	1	43.578	1.288	0.320	0.244
	0.05-0.212 mm	45.982	1	45.982	1.347	0.310	0.252
	MWD-mm	0.041	1	0.041	2.133	0.218	0.348
	<2 mm_OC%	0.481	1	0.481	8.900	0.041	0.690
	0.212-2 mm_OC%	0.766	1	0.766	8.354	0.045	0.676
	0.05-0.212 mm_OC%	0.147	1	0.147	1.064	0.361	0.210

Appendix 6.23: Multivariate analysis of variance (MANOVA) for the measured parameters between 0 – 30 cm and 30 – 60 cm soil depths in NT in the long-term

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L2_NT depth	<2 mm	3.872	1	3.872	0.117	0.750	0.028
	0.212-2 mm	0.400	1	0.400	0.010	0.926	0.002
	0.05-0.212 mm	3.315	1	3.315	0.081	0.791	0.020
	MWD-mm	0.001	1	0.001	0.078	0.794	0.019
	<2 mm_OC%	1.723	1	1.723	61.529	0.001	0.939
	0.212-2 mm_OC%	1.175	1	1.175	65.128	0.001	0.942
	0.05-0.212 mm_OC%	0.826	1	0.826	4.876	0.092	0.549

Appendix 6.24: Multivariate analysis of variance (MANOVA) for the measured parameters between 0 – 30 cm and 30 – 60 cm soil depths in CT in the long-term

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
L2_CT depth	<2 mm	89.398	1	89.398	12.671	0.024	0.760
	0.212-2 mm	2.245	1	2.245	0.269	0.631	0.063
	0.05-0.212 mm	105.085	1	105.085	6.655	0.061	0.625
	MWD-mm	0.037	1	0.037	10.044	0.034	0.715
	<2 mm_OC%	0.297	1	0.297	0.491	0.522	0.109
	0.212-2 mm_OC%	0.269	1	0.269	1.036	0.366	0.206
	0.05-0.212 mm_OC%	0.697	1	0.697	4.207	0.110	0.513

Appendix 6.25: Multivariate analysis of variance (MANOVA) for the measured parameters between short-term and long-term NT

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
NT duration	<2 mm (0 –30 cm)	208.153	1	208.153	28.153	0.006	0.876
	0.212-2 mm (0 –30 cm)	10.747	1	10.747	0.800	0.422	0.167
	0.05-0.212 mm (30 cm)	243.334	1	243.334	70.348	0.001	0.946
	MWD-mm (0 –30 cm)	.039	1	.039	4.539	0.100	0.532
	<2 mm (30 –60 cm)	313.493	1	313.493	11.789	0.026	0.747
	0.212-2 mm (30 –60 cm)	1.402	1	1.402	0.018	0.900	0.004
	0.05-0.212 mm (30 –60 cm)	136.899	1	136.899	2.848	0.167	0.416
	MWD-mm (60cm)	0.055	1	0.055	4.407	0.104	0.524
	<2 mm_ OC% (0 –30 cm)	0.826	1	0.826	23.099	0.009	0.852
	0.212-2 mm_ OC% (0 –30 cm)	0.599	1	0.599	40.692	0.003	0.910
	0.05-0.212 mm_OC% (0 –30 cm)	0.186	1	0.186	2.619	0.181	0.396
	<2 mm_ OC% (30 –60 cm)	0.001	1	0.001	0.024	0.884	0.006
	0.212-2 mm_ OC% (30 –60 cm)	0.026	1	0.026	0.323	0.600	0.075
	0.05-0.212 mm_ OC% (30 –60 cm)	0.065	1	0.065	0.342	0.590	0.079