

Impact of conservation agriculture practices under a decade of tillage, crop rotation and crop residue management systems on selected soil physical properties and simulated soil erosion on a Haplic Plinthosol

COSSY SHAYNE NONXUBA

201822111



AGS 701: MSc Agriculture: Soil Science

Department of Agronomy

University of Fort Hare
Faculty of Science and Agriculture

Supervisor: Prof A Manyevere

Co-supervisor: Dr DE Elephant

University of Fort Hare

Alice

South Africa

2024

DECLARATION

I, **Cossy Shayne Nonxuba**, declare that the content of this thesis hereby submitted for Master of Science Degree (MSc) at the University of Fort Hare is my work, with the exception of particular references attributed to their authors, and that this thesis has not been previously submitted for an academic degree to this institution or any other institutions of higher learning.

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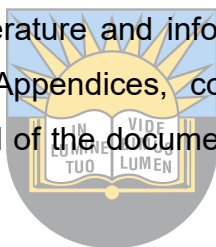


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PREFACE

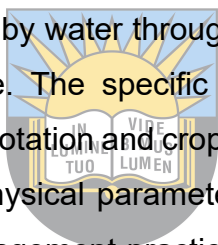
This document starts with a general abstract, followed by five Chapters that are separated but linked. Chapter 1 provides a brief of background information, problem statement, justification and purpose of the study. Chapter 2 overviews the available literature about the research problem and the effects of conservation agricultural components on selected soil physical properties, soil erosion through soil loss and runoff as well as the effect of time in soil rehabilitation through conservation agriculture. Chapters 3 and 4 contain two main objectives reported in manuscript format, with individual abstract, introduction and aim, study methodology, results, and discussion. Chapter 5 discusses the link between the two experimental chapters and provides general conclusions with recommendations from the identified gaps in the study. Although the Chapters have been separately reported, they originate from a common objective hence repetition among chapters could not be completely avoided. The literature and information cited in the document is all presented in the reference list. Appendices, comprising of additional yet related information, are provided at the end of the document (Anova, mean tables and graphs/figures).



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GENERAL ABSTRACT

The effects of conservation agriculture (CA) are not instant but are gradually visible with time of implementation from short, medium to long term. Conventional agriculture and inappropriate agronomic practices by farmers especially small-scale growers (SSG) are common in the Eastern Cape Province. Government interventions or strategies to boost the implementation of CA have failed to yield desired results. This led to exacerbated soil degradation rates overtime, as soils of the Eastern Cape are highly susceptible to degradation due to their mineralogy of low organic matter, and shallow depth. The general aim of the study was to evaluate the effect of tillage management practices, crop rotations comprised of maize (*Zea mays*), wheat (*Triticum aestivum*) and soybean (*Glycine max*) crops associated with different crop residue management practices on selected soil physical properties and soil erosion by water through runoff and soil loss after a decade of CA in the Phandulwazi ecotope. The specific objectives of the study were to (i) investigate the effect of tillage, crop rotation and crop residue management practices after a decade of CA on selected soil physical parameters, (ii) simulate the effect of tillage, crop rotation and crop residue management practices after a decade of CA on soil loss and runoff.



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The evaluation was done on a CA field trial that began in 2012 and still on-going. The experiment was designed in a split split-plot trial structure with 3 replicate blocks comprised of 16 treatment combinations. The main, sub and sub-sub plots were allocated to tillage [no-tillage (NT) and conventional tillage (CT)], crop diversification [maize-fallow-maize (MFM); maize-fallow-soybean (MFS); maize-wheat-maize (MWM); maize-wheat-soybean (MWS)] and crop residue management [residue removal (R-) and residue retention (R+)], respectively. Soil samples from 0 – 10, 10 – 20 and 20 – 30 cm depths were collected from the CA trial after twenty-three (23) cropping seasons (2012 – 2023/24).

Significant responses were observed mostly on NT plots subjected to rotation of MWM and MWS crops. Soil physical properties [bulk density (BD), particle density (P_s), mass wetness (θ_m), volumetric water content (θ_v), porosity (ϕ), saturated hydraulic conductivity (K_s), mean weight diameter dry & wet (MWD_{dry} & MWD_{wet}), and stability index (SI)]

were affected by CA strategies in the medium term (+ten years). Tillage practices showed a dominant significant effect (NT plots greatly improved soil physical properties than CT) over crop rotations and residue management on BD, ϕ and aggregate stability (AGS). Soybean rotation treatments (MFS and MWS) had a significant effect on BD and AGS (i.e. it reduced BD and enhanced AGS), likely due to the quick decomposition of soybean residues, indicating potential improvements in soil health and soil quality with legume inclusion in rotations. Additionally, residue-retained plots had higher θ_m and θ_v due to the substantial amount of SOM returned by residue decomposition. There were no significant differences observed in Ks, which could be attributed to the nature of the particle size distribution, as water moves more easily on sandy soils. These medium-term results present continuous benefits from proper implementation of CA in sustainable farming and resource conservation.

Soil loss and runoff were low for all treatment plots under no-tillage system as the practice reduces soil erosion that is caused by tillage farming, especially in sandy loam soils. Runoff and soil loss were both significantly higher in MFM (subplot subjected to monocropping) followed by MFS (subplot under rotation of two crops) and lowest in MWS (subplots under crop rotations of three crops). Residue retained treatment plots registered low soil loss & runoff because of better soil structure and aggregation as the binding products (formed during decomposition) merge soil particles, thereby reducing sediment deployment. These results signify CA benefits in soil conservation and sustainable farming for the present and future agricultural produce. Moreover, this study correlated soil properties with soil loss and runoff thereby elucidating significant role played by soil structural indices on soil erodibility. BD and θ_m predicted soil loss with high correlation coefficient (R^2) and low root mean square error (RMSE); thus, suggesting a strong reliability. Further evaluation and validation of the developed model however remains crucial. Investigation of soil erosion and measuring nutrient loss within sediment deposition is ideal for future studies.

Key words: Bulk density, conservation agriculture, soil degradation, soil erosion, soil physical properties.



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ACKNOWLEDGEMENTS

The valuable contributions from several individuals that led to the success of this work is highly acknowledged.

My sincere gratitude goes to my supervisor, Prof. A Manyevere, and co-supervisor, Dr DE Elephant. Thank you for making it all possible, your assistance and guidance certainly led to the completion of this study. I extend my authentic appreciation to Agriseta bursary for funding my 1st year of study, the National Research Foundation (DST-NRF) for funding my 2nd year of study, and the project funding from the New Zealand Government.

I am thankful of the support I received from the staff and interns of the University of Fort Hare, particularly the Agronomy Department, and Phandulwazi Agricultural High School. I specifically wish to mention Miss X. Mngadi, a former senior lab technician; Mr S. Bobotyana, the research technician; Miss A. Mgadi, the former intern; Miss A. Madikane, the research technician; Mr T. Mphakhamisi, the field technician and Mr Mbambo the Phandulwazi Agricultural High School farm manager.

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I extend my appreciation to my former colleagues for their assistance towards the accomplishment of this study.

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CHAPTER ONE

Background

1.1 Introduction

Soil degradation is a critical environmental problem throughout the world's arable land ecosystems including in South Africa (SA) (Hishe *et al.*, 2017; Hammad *et al.*, 2018). It poses a threat to sustainable agriculture and damages agricultural fields such as crop fields, pastures, forests as well as natural ecosystems if it is not properly managed (Le Roux, 2011). Zingore *et al.*, (2015) reported that Sub-Saharan Africa (SSA) has considered 65% of its land area to be degraded. Crop management practices like conventional tillage, mono-cropping and crop residue removal are commonly practiced under smallholder farming systems and are known to cause soil degradation (Lal, 2015). Soil physical degradation comprises processes of soil compaction, surface crusting, soil erosion, structural decline, and waterlogging, all negatively affecting soil physical properties, yields and agricultural productivity (Deborah *et al.*, 2008). Soil physical degradation interferes with soil hydrology and plant's access to water thereby reducing crop productivity (Molden *et al.*, 2007). Proper management of arable lands are crucial to food production within the persistent growing population. South Africa's arable land account for about 10 to 12% of the total land surface (Strauss *et al.*, 2021a) but only 3% is considered to have high productivity potential (Laker, 2005). Studies have predicted about 70% and more of the country's land to be affected by various soil erosion intensities which degrades the soil (Le Roux *et al.*, 2007; Van Antwerpen *et al.*, 2023). The process of soil erosion occurs naturally; however, it is frequently influenced by human pressure through activities such as the removal of vegetation that covers the ground as well as overgrazing that leaves the surface bare (Oldeman, 1992; Van Antwerpen *et al.*, 2023). Soil erosion occurs gradually, often when wind or water forcefully detaches soil particles, leading to deterioration. Water run-off can be a result of surface crusting in cultivated soils which contributes to erosion through soil detachment and aggregate disintegration by precipitation (Le Bissonnais, 1996). Nutrients and valuable soil biota are transported during runoff, and the biodiversity is considerably reduced, thereby impeding the quality of soil.

Soil structure and water availability have adversely been affected by intensive tillage, monoculture-based crop production and removal of crop residues in many South African soils (Haruna and Nkongolo, 2019). The extent of soil degradation due to tillage is affected by clay content and mineralogy of the soil (Manyevere *et al.*, 2016). Chivenge *et al.*, (2007) reported that soil tillage facilitated the depletion of soil organic matter (SOM) significantly on sandy soils as opposed to clay soils. This was because of sandy soils lacking the physical protection of SOM than clay soils. The loss of SOM contributes to reduced biological activity on soil and a possible increase in soil physical degradation over time. Soil organic matter helps in soil structural improvement, reverse soil erosion, and enhances soil moisture through its hydrophilic properties (Busari *et al.*, 2015; Pareja-Sánchez *et al.*, 2017; Munera-Echeverri *et al.*, 2020).

South African soils within the Eastern Cape Province, are extremely fragile and vulnerable to degradation because of their mineralogy and very high fine sand fractions (Manyevere *et al.*, 2016). These soils lack in both clay and oxide contents, their aggregation therefore fully depends on SOM (Duiker *et al.*, 2003; Devine *et al.*, 2014). Agronomic practices such as no-tillage system sustainably conserves the soil, enabling SOM accumulation, hence improving soil quality and biodiversity (Zuber *et al.*, 2018). Conservation practices such as rotational cropping and crop cover that improve infiltration and water storage capacity of the soil help increase water availability for productive transpiration and crop yields (IWMI, 2006). Interventions that are synergistic, such as the maintenance of soil quality and improved water management have the highest potential to improve soil hydrology (Deborah *et al.*, 2008).

Managing arable land, soil and water closely associates and corresponds to one another (Deborah *et al.*, 2008). Conservation agriculture (CA) is a recommended sustainable farming approach that improves soil structure, soil aggregate build-up and enhance crop yields with reduced input costs (Swanepoel *et al.*, 2018). The CA practise has been advocated to better soil properties, water movement and could buffer soil resilience against climate change through correct implementation of its three linked CA principles: (1) no-tillage system, (2) rotational cropping or diversified cultivation and (3) crop residue

retention as ground cover, especially with legume crop inclusion (Giller *et al.*, 2009; FAO, 2018). The provincial government within the Eastern Cape province formed strategic schemes with the objective to promote CA and improve its adoption in small scale farming sector (Muzangwa *et al.*, 2021). Short term effects of CA are facilitation of early planting, increased infiltration, reduced evaporation, soil temperature and labour for land preparation (Erenstein, 2002; Deng *et al.*, 2006; Alliaume *et al.*, 2014). Long term CA effects are reduced erosion, increased SOM, increased N mineralization and aggregation (Sithole *et al.*, 2019). According to Wang *et al.*, (2023) diversified cropping patterns with a minimum of three varying plant species with the inclusion of legumes within the rotations contributes to improved soil N-fertility. The productivity of farmlands depends on soil, water, and biological resources' conservation for the present and future produce. A programme to spread awareness and improve the implementation of CA within the province was the establishment of the Conservation Agriculture Thrust (CAT) jointly by the University of Fort Hare coupled with the provincial department of agriculture (ECDRDAR) targeting agricultural extension specialists and farmers (Muzangwa *et al.*, 2021). The adoption of CA is limited due to different limiting factors to its practice.

The results from studies relating to soil physical properties are inconsistent. Several authors reported cover crops to enhance bulk density and moisture on different soils (Dabney *et al.*, 2001; Fageria *et al.*, 2005; Villamil *et al.*, 2006). Others observed crop cover to variously impact soil strength (Grant and Lafond 1993; Osunbitan *et al.*, 2005; Abiven *et al.*, 2009). Mosaddeghi *et al.*, (2009) noticed a reduction in bulk density (BD) under a no-tillage (NT) practice than conventional tillage (CT). In contrast, Zuber *et al.*, (2015) detected an increased BD on NT over CT. Jabro *et al.*, (2016) and Laghrour *et al.*, (2016) however, reported no variations among CA and CT treated soils under similar conditions. The contradictory results are because soil responds different to agronomic practices as influenced by climate, soil form and SOM (Mupambwa and Wakindiki, 2012). The duration of the practice likewise impacts significantly, its effects on soil are apparent in the medium to long term and may vary from soil types. The CA practice is conceptualized to result to improvements in soil physical properties through reduced soil

disturbance and improved structure, aggregation and resistance to degradation forces (Richards *et al.*, 2014; Nyambo *et al.*, 2022).

Problem Statement

Unsustainable agricultural practices such as mono-cultural crop production, soil tillage and residue removal increase soil physical degradation together with soil loss and runoff. Soil degradation is a concerning threat in agricultural crop productivity for both the present and future agronomic produce. Provincial government attempts to introduce CA in the Eastern Cape have not yielded desired results, farm experience has shown that advances in soil properties and yields as affected by CA are not immediate and not in a consistent manner (Nyambo *et al.*, 2022), this is also influenced by the poor adoption of CA resulting from lack of knowledge, lack of resources, poverty and different utilization of residues by small holder farmers which leads to improper implementation of the CA principles. Consequently, some farmers especially within the small-scale often become unwilling to continue with the CA system (Giller *et al.*, 2009). The report from other countries in Sub-Saharan Africa coincides with this, where CA adoption has been found to be very low (Giller *et al.*, 2009). South African farmers have adopted the CA principles individually at more than 40% rate. However, only 14.2% have fully adopted the practice (Findlater *et al.*, 2019), with adjustments to 25% in 2020 (Strauss *et al.*, 2021a). Time plays a significant role in soil re-integration through CA practices, it is therefore important to monitor the duration as the practice requires long term. Most conducted studies focused on short term effect of CA. There is a scarcity of research on the medium to long-term effect of conservation agricultural practices on soil physical properties, and soil erosion by water in the Eastern Cape.

Justification of the study

Conservation agriculture is essential in managing soil degradation and soil loss through surface runoff. It is necessary for farmers managing soil physical properties, quality, and fertility or productivity to know the long-term effects of conservation agriculture on soil status (Mtyobile *et al.*, 2020), to make sound recommendation on the utilization of conservational approach in farmlands of the Eastern Cape Province. Hatfield *et al.*, (2001)

predicted that agricultural productivity could increase up to 25 – 40% through adequate soil conservation measures like minimum soil disturbance, to enhance water infiltration and water holding capacity of the soil, and between 15 – 25% with proper fertility management. In recent years, CA has been promoted as a sustainable, strategic practice to achieve a sustainable agricultural system (Dube *et al.*, 2013). The latest study conducted in the South African haplic cambisol investigated the short-term CA effects on selected soil physical properties (Nyambo *et al.*, 2022). However, very few studies have systematically documented the effects of CA on soil physical properties and erosion for the medium to long term implementation within the region, this study seeks to investigate the effects of CA after it has been implemented for a series of years with different seasons. The short-term research may not capture the full benefits of CA, as it requires time to significantly affect soil properties. The full potential of soil and water can be achieved by proper management of resources at the farm level in rain-fed areas, this will have a great impact in developing countries as most farmers produce under rain-fed (Wani *et al.*, 2009). This study is focused on how selected soil physical properties and soil erosion is affected by tillage, crop rotation and crop residues management practices overtime.



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1.2 Objectives:

The general objective of this study was to investigate the tillage management practices, crop rotations involving soybean, wheat and maize crops, as well as varying residue management effects on soil physical properties that were selected and soil-water erosion after a decade of conservation agriculture in the haplic plinthisol of Phandulwazi ecotope. The study specifically aimed:

1. To investigate the effect of conservation agriculture after a decade of tillage, crop rotation and crop residue management practices on; (i) bulk density, particle density and porosity, (ii) gravimetric water content, volumetric water content, and saturated hydraulic conductivity, (iii) structural aggregate indices (MWD_{dry}, MWD_{wet} and stability index) on a Haplic Plinthosol.

2. To determine the effect of conservation agriculture after a decade of tillage, crop rotation and crop residue management practices on simulated (i) soil loss and (ii) runoff on a Haplic Plinthosol.

1.3 Hypothesis

1. A decade of CA practices improves soil; (i) bulk density, particle density and porosity, (ii) gravimetric water content, volumetric water content, saturated hydraulic conductivity, and (iii) structural aggregate indices (MWDdry, MWDwet, stability index).
2. A decade of tillage, crop rotations and crop residues management practices reduce (i) soil loss and (ii) runoff.



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CHAPTER TWO

Literature review

2.1 Introduction

The maintenance and enhancement of soil quality within the agro ecosystems is a major objective of conservation agricultural (CA) practice. This chapter revises the literature concerning the sources and impacts of soil physical degradation in arable land ecosystems as a leading factor in soil productivity and yields reduction, surface runoff & soil erosion. The selected soil physical properties were reviewed with emphasis on CA principles/ components pertaining their reintegration for high quality soils capable of optimum crop production and key practices to their sustainability. This chapter is arranged in a manner corresponding to its specific aims to ensure relevance to the study gap. The review provides a strong insight of the available data and significance of the study.

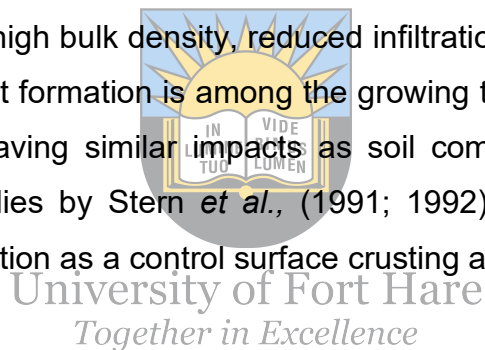
Soil physical properties

Common and mostly investigated physical properties of soil with high impact on agricultural management include but not limited to soil colour, soil texture, soil structure and aggregation, soil porosity, soil density and consistence (Osman, 2012). Soil physical properties affect all the ecosystem services, and crop production, especially those linked with compaction (i.e., soil bulk density, porosity, water infiltration and penetration resistance) as they affect root elongation, seedling emergence and crop productivity at large (Humberto and Sabrina, 2018). Soil texture as a fundamental property of the soil and structure (by virtue of aggregation) regulate porosity, bulk density, compaction, moisture and aeration in the soil (De Lima *et al.*, 2022). Texture is not usually altered by agronomic management practices. However, it may be changed from the processes of erosion, soil deposition or translocations, and human pressure (i.e. deep ploughing and/or land levelling) (Boix-Fayos *et al.*, 2001; Osman, 2012). Lado *et al.*, (2004) on research on Spanish soils suggested improvements in soil aggregation with clay particles, whereas Mills and Fey, (2004) reported that clay content minimally impacted surface crusting in South Africa. Surface crusting is influenced by various mechanisms (agronomic practices and surface pressure influencing compaction) as well as distinct soil properties (quality;

aggregate, pore distribution and stability), hence their inconsistent relationship with soil texture (Nciizah and Wakindiki, 2014).

Soil structure and Compaction

Soil structure is affected by both natural processes such as soil saturation, dry stress, freeze and thaw actions, as well as human induced agronomic practices of cultivation (Eash *et al.*, 2015). It is mainly the orderly compilation of soil pedes within a soil profile. Poor soil structure is observed through soil compaction, which is a threat concerning the modern mechanized farming, globally (Laker, 2001; Laker and Nortjé, 2020). Mitchell and Berry, (2001) reported that clay content lower than 15% in the topsoil results in increased risk to compaction. Soil compaction impacts negatively on crop cultivation and the frequently noted impacts are poor crop water productivity, crop wilt and reduced crop yields (Laker, 2005; Laker and Nortjé, 2020). Smith, (1992) explained compaction to result in surface crusting, high bulk density, reduced infiltration and soil moisture as well as poor soil aeration. Crust formation is among the growing threats in the South African farmlands (Figure 2.1), having similar impacts as soil compaction (Laker and Nortjé 2019). South African studies by Stern *et al.*, (1991; 1992) has documented positive returns from mulch application as a control surface crusting and soil compaction.



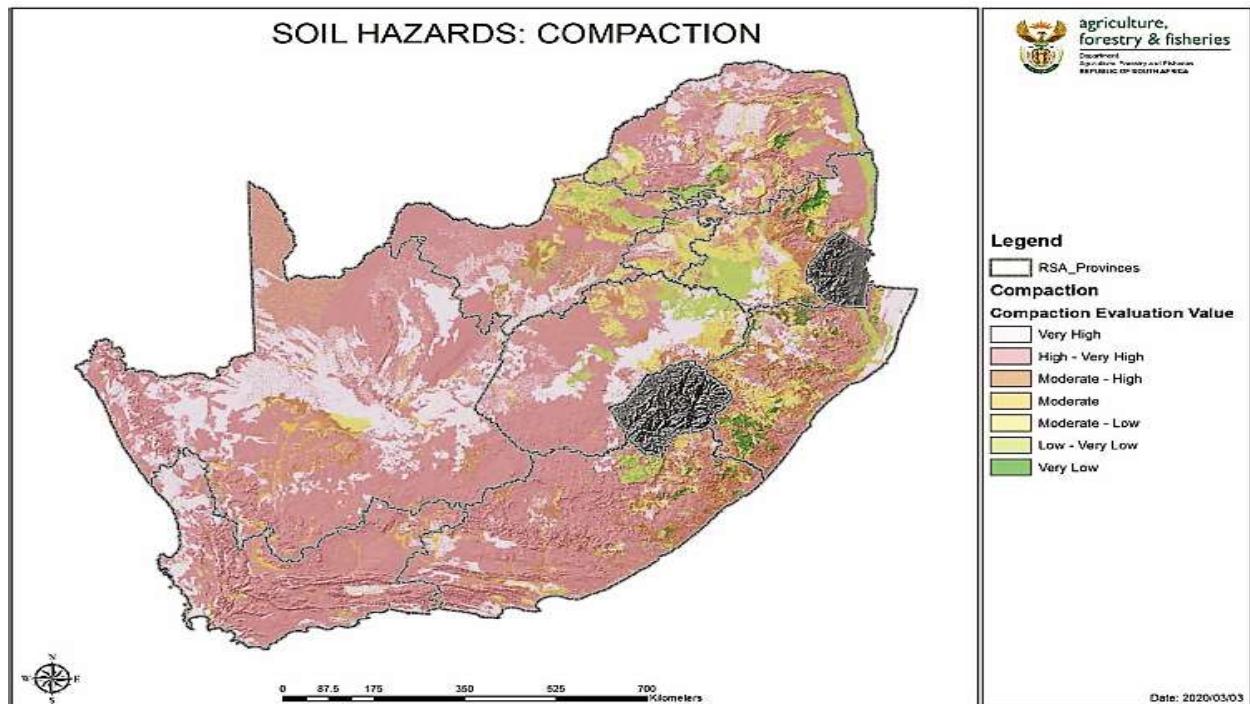


Figure 2. 1: Extent of compaction within the South African country (DAFF, 2017)

Soil bulk density (BD)

Bulk density (BD) is defined as the weighed volume of dry soil, it is obtained by dividing the dry soil weight by its volume. BD is a proxy of compaction and expresses the extent of soil structural aggregation. BD affects the soil's permeability, moisture retention, pore distribution and nutrient availability (Indoria *et al.*, 2020). BD ranges between ± 1.0 to 2.0 g cm^{-3} (Osman, 2012), sandy soils have a relatively high BD ranging from $1.3 - 1.7 \text{ g.cm}^{-3}$. Soil BD is influenced by SOM, particle size distribution, structural aggregation, and pore size distribution (Brady and Weil, 2002). Reduced BD cause weak root anchorage, yet an increased BD lowers the processes of soil gaseous exchange (Lampurlanés and Cantero-Martínez, 2003), negatively influencing the rates of saturated hydraulic conductivity (K_s) and soil permeability (Bhattacharyya *et al.*, 2006; Miriti *et al.*, 2013). Several authors reported that crop cover reduces BD thereby enhancing soil hydraulic properties (Fageria *et al.*, 2005, Villamil *et al.*, 2006). Also, NT system is reported to decrease BD when in contrast with CT (Mosaddeghi *et al.*, 2009), this result from the improved soil structural aggregation with enhanced pore distribution as influenced by reduced soil disturbance on NT than in CT. Nonetheless, Zuber *et al.*, (2015) on a study on both CT and NT found more BD on NT. Nebo *et al.*, (2020) explained BD to be influenced by the crop root type

as well as the decomposing rates of various crop residues as various roots penetrate through the soil, affecting soil structural aggregation, stability and hence forming peds that resist compaction resulting in reduced BD. The decomposition rate, on the other hand, influences the amount of SOM within the soil; responsible for aggregate build up and stability whilst reducing BD.

Porosity (ϕ)

Porosity relates to spaces (pores) within soil aggregates that are either filled with air or water (Osman, 2012). The implementation of CA was observed to effectively influence soil pore and particle size distribution (Jensen *et al.*, 2019). Studies on short-term CA effects have documented a drop in soil's total porosity and macro porosity, respectively, since CA initially contributes to increased BD and hence reduced porosity (during the early stages of conversion from CT to NT) (Soracco *et al.*, 2018). Mangalassery *et al.*, (2015) within the United Kingdom observed that no-till practice after 7 years of implementation showed a 47% reduction in porosity on the topsoil. Unpleasantly, the drop in macro porosity and observed rise in micro porosity reflects compaction within the short term (Kichey *et al.*, 2007). In contrast, the extended term of CA farming practice increased the soil's porosity on certain studies (Pires *et al.*, 2017; Borges *et al.*, 2018). In Brazil, noticeable improvement in total porosities were found in 25 years (Pires *et al.*, 2017) and after three decades of CA adoption in Argentina (Tavares and Tessier, 2009).

Soil aggregate stability (AGS)

AGS gives information about soil structure in relation to water retention, resistance to soil erosion by water, water infiltration, the presence of carbonates and gypsum, and storage of SOC in the soil (Xiao, 2015; Zheng *et al.*, 2018). Crop residue removal affects aggregate stability by inducing soils susceptibility to surface sealing and crusting (Blanco-Canqui and Lal, 2009). Conventional tillage (CT) is well known to disintegrate the surface soil (Lipiec *et al.*, 2006; Schlüter *et al.*, 2019), while the adoption of no-tillage (NT) preserves and amends aggregate's development and resistance (Li *et al.*, 2019). Several studies highlighted improvements in aggregate stability within the topsoil to result from CA practices (Rocha *et al.*, 2020). Li *et al.*, (2019), on a meta-analysis presented 31% of soil aggregates as more stable under conservation agricultural practice than conventional

agriculture. A Chinese study by Song *et al.*, (2019) projected great improvements of 35.18%, and 33.52% in large and small soil macro aggregates, respectively, as well as a 25.10% enhancement in micro aggregates, within the topsoil. Kavdir *et al.*, (2005) observed the development of pore size distribution and AGS improvement facilitated by the leguminous soybean on CA through its quick decomposition that adds OM which enhances soil quality by improving structural aggregation, stability and porosity. Prominently, literature projects the cumulative effects of conservation agricultural system as prominent in the medium to long term adoption (Li *et al.*, 2019), (Blanco-Canqui and Ruis, 2018), (Nyambo *et al.*, 2022).

Soil hydraulic conductivity (Ks) and soil moisture

Hydraulic conductivity (Ks) relates to the soil's capability in transmitting water under saturated or nearly saturated condition (Meter group, 2017). High BD and low porosity (ϕ) negatively influence Ks (Gicheru *et al.*, 2004; Miriti *et al.*, 2013). Mwendera and Feven, (1993) noticed Ks to directly reduce with an increase in soil compaction. Research by Nebo *et al.*, (2020) in the short duration (after 3 years) showed less significant responses on compaction and moisture indices in Eastern Cape. Research shows contradictory trends in the influence of CA practices on Ks (Hu *et al.*, 2009). Moreno *et al.*, (1997) and Medina-Sauza *et al.*, (2019) explained that high Ks on NT than CT was because of the presents of special paths due to earthworm activities as they influence soil structural build-up and porosity as well as moisture availability. According to Kodešová *et al.*, (2009) and Kargas *et al.*, (2012) enhanced soil structural aggregation, pore distribution, roots and SOM accumulation contributes to higher Ks under NT. Report by Six *et al.*, (1998) showed a lower Ks in CT plots because of soil disturbance during cultivation, which leads to soil degradation.

Soil moisture can be presented through volumetric or gravimetric water content. It is the measure of the extent to which the soil is at saturation through volume or mass weighing. The commonly used method of testing soil wetness is the gravimetric approach. Study of soil moisture is essential for daily agricultural operations (Osman, 2012).

2.2 Soil loss

Soil loss is the degradation problem faced by land and water resources management globally. About 84% of degradation in land areas result from soil erosion, across the globe, 56% being due to water erosion and 28% being erosion by wind (Oldeman, 1992). South African soils have low resilience and are prone to degradation (Njaimwe *et al.*, 2018). The Eastern Cape is one of the provinces in South Africa with high rates and susceptibility to degradation through soil loss and runoff (Le Roux *et al.*, 2008). Gully and sheet erosion are shared challenges in small-scale farmers, yet wind and salinity are challenges faced by farmers in the large/ commercial sector (Njaimwe, 2010). Water erosion is the chief degrading force in this region, this was observed from the shallow and vulnerable soils of Eastern Cape (Fox & Rowntree, 2001). Despite the inappropriate agronomic practices, some fields have inclined slopes (Fox and Rowntree, 2001), as such, the susceptibility to erosive forces and deposition/ translocation by water runoff is greatly increased due to severe surface runoff of high velocity with great strength to detach/ erode the soil (Laker, 2004). Furthermore, degradation is increased by human pressure on the land. High population density (averaging 90 people/ km²) in the Eastern Cape smallholder sector leads to more degradation and hence susceptibility to hydric erosion in contrast to large-scale farming sector (ranging at 20 people/km²) with minimal pressure (Van Averbeke *et al.*, 2006). South African estimations by Le Roux *et al.*, (2008) has shown 12.3 t ha⁻¹ yr⁻¹ to be the rates of soil loss, the Eastern Cape Province having the highest soil loss (Figure 2.2), only 0.25 – 0.38 t ha⁻¹ yr⁻¹ being the soil development rates (Matthee and Van Schalkwyk, 1984). Australia has only 4.1 t ha⁻¹ yr⁻¹ comparative rate of degradation (Le Roux *et al.*, 2008). Although the two countries differ in environmental conditions significantly, South Africa must control its rate of soil loss on arable land (Van Antwerpen *et al.*, 2021). CA has the potential to reverse the degradation of arable lands and reintegrate the already affected areas (FAO, 2018). Ethiopian studies reported an increase in soil loss by CT as compared with minimum tillage with crop cover maintained, (Woyessa and Bennie, 2004; Erkossa *et al.*, 2005; Kurothe *et al.*, 2014; Haregeweyn *et al.*, 2016; Adimassu *et al.*, 2019; Molla and Desta, 2022).

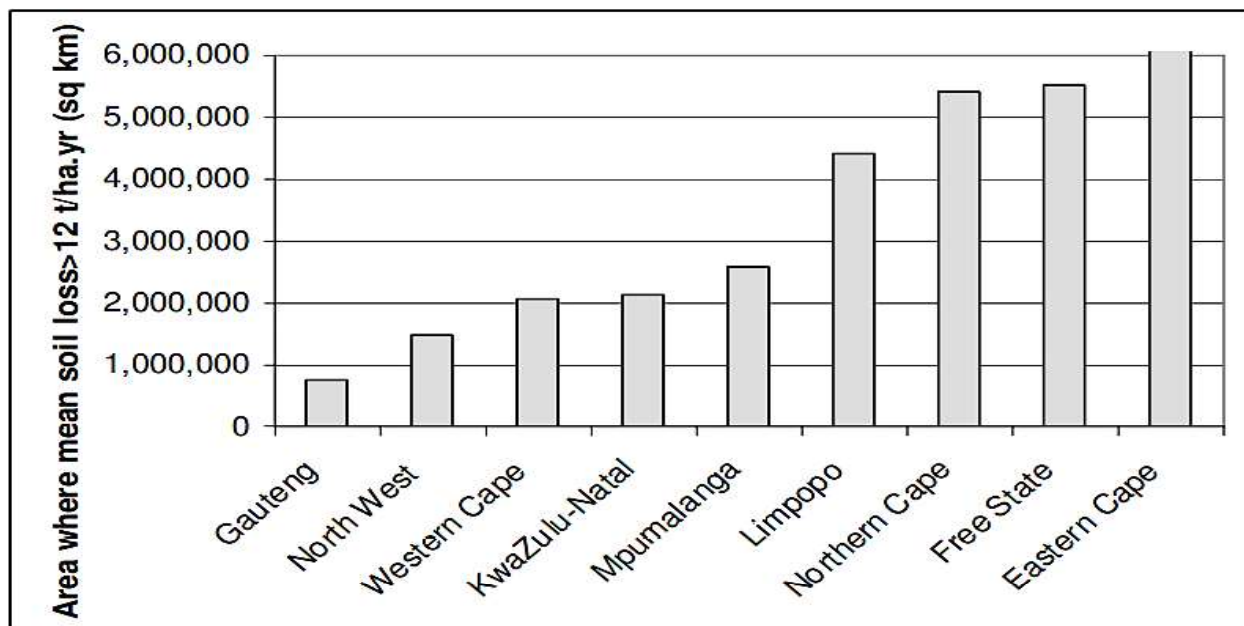


Figure 2.2: Provincial presentation of areas with annual mean soil loss greater than 12 t/ha.yr (Le Roux, 2011)



2.3 Run-off

Water is the main cause of erosion within the South African land surfaces (Le Roux *et al.*, 2008; Baade *et al.*, 2024). Water erosion result from rainfall, in un-directed and directed surface flows as either sheet, rill or gully erosion, respectively. It is difficult to identify sheet erosion, unlike the rill and gullies that are clearly visible. Researchers identify sheet erosion as the chief contributor to soil loss deposition all over South Africa (Le Roux, 2011). Soil loss by water erosion is influenced by the interactive effects and combination of rainfall intensity, soil susceptibility, topography, cultivation, and support practice. Wischmeier and Smith, (1978) formulated these five components of the Universal Soil Loss Equation (USLE). Conservation agricultural practices (especially in the long term) enhance soil moisture and reduce surface run-off (Jat *et al.*, 2018). Research by Mhazo *et al.*, (2016) on a global meta-analysis indicated 60% soil loss and 40% runoff coefficients to be lesser on no-till system. Blanco-Canqui and Ruis, (2018) observed a 17% – 86% improved permeability on no-tillage practice. Likewise, Alvarez and Steinbach, (2009) found improved water percolation under CA system.

2.4 Time as a factor of soil reintegration through conservation agriculture

Soil physical properties change gradually, and they do not occur consistently (Nebo *et al.*, 2020). Conservation agriculture is a long-term adaptation measure (González-Sánchez and Basch, 2017). Studies established that bulk density takes a prolonged duration to be affected by a conservation agricultural system. Gura and Mkeni, (2019) as well as Ferreras *et al.*, (2000) found no differences on BD between a conservation and conventional system of tillage. BD responses are not sudden, yet they do not respond consistently (Ordoñez-Morales *et al.*, 2019).

The findings from a short-term study by Gura and Mkeni, (2019) presented NT to enhance soil bio-chemical indices (i.e. soil organic carbon (SOC), microbial biomass carbon (MBC), β -glucosidase (BG) activity, extractable P and K, soil pH, and electrical conductivity (EC)) when contrasted with CT, whilst soil physical properties (BD and AGS) showed no improvements. Numerous reports presented high BD on NT than CT (Govaerts *et al.*, 2009; Cheesman *et al.*, 2016). However, CA systems are believed to increase BD in short term as in the findings by Gura and Mkeni, (2019) where a high soil aggregate stability (AGS) under CT than NT was observed, and this could be resulting from the study's limited duration (three years). Reduced disturbance with retention of soil cover under the NT practice led to soil development in the top-surface layer. The short-term observations showed crop diversification to need more extended periods to significantly affect soil indices. Crop diversifications suggested that fallow practices had improved structure than continuously cultivated plots (Gura and Mkeni, 2019). The insignificant responses from a retained crop cover treatment identified with BD and soil aggregate stability are likewise due to the limited duration of the practice in this experiment.

Enhanced soil attributes in NT overtime are expected from the influence of SOM accumulation that further improves aggregation, soil resistance and BD. Caesar-TonThat *et al.*, (2011) reasoned that AGS in areas with surface cover improves as influenced by stimulated activity of microbes and production of binding products during decomposition processes. Observation in the long-term studies however contradict; research by Nunes *et al.*, (2020) on analysing CA impacts overtime found high BD on NT than CT. Conversely, the variations were absent after a decade. BD is believed to increase in the

short term of NT, until it reaches equilibrium, and the structure develops, then proceed reduction afterwards resulting to less BD on NT with well aggregated soil than CT in the long term (Kinsella, 1995; Nyambo *et al.*, 2022). The long-term CA practice is expected and known to be positively effective in sustainable soil development.

2.5 Conservation Agriculture in Eastern Cape Province

Conservation agriculture is an agronomic approach which sustainably promotes no-tillage, crop diversification and retention of residues (Muzangwa *et al.*, 2021). The CA approach aims in sustaining water and soil resources to improve the quality, enhance fertility and maximize yields (Delgado *et al.*, 2011; Sithole *et al.*, 2016). It facilitates diverse species inhabitant, hence improves soil processes on and in the soil matrix, contributing to maximized water availability, nutrient accessibility as well as enhanced agricultural productivity (FAO, 2021). The CA system encompasses principles that are inter-linked and require simultaneous adoption; no-tillage system that sustains SOM, and enhance nutrient concentrations (Dube *et al.*, 2012); crop rotation which includes interchanging of different crops, helps combat pest and pathogenic related challenges while enhancing fertility (Derpsch and Friedrich, 2009); and crop residue retention that enhances soil hydraulic conservation and control soil erosion risks (Thierfelder and Wall, 2009).

Africa has only about 0.3% of land with CA adoption. Kassam *et al.*, (2015) estimated the area to have improved from 2008 to 2013. South Africa was estimated in 2008 to have 368 000 hectares under CA, with no increase in 2013 (Kassam *et al.*, 2015). The implementation of individual CA components in SA is more than 40% (Findlater *et al.*, 2019). However, very few growers implement the 3 principles concurrently, accounting for 14.2% of the total farmers (Findlater *et al.*, 2019), (Strauss *et al.*, 2021b) has revised it to 25% in 2020. Establishment of the Conservation Agriculture Farmer Innovation Programme (CA FIP) in 2013, was one of the key strategic thrusts in sustainable production (Smith, 2023). The Massive Food Production and Land Care schemes by the department (Makara, 2010), were some of the initiated strategic approaches to spread the adoption of CA (Muzangwa *et al.*, 2021). Likewise, the establishment of Conservation Agriculture Thrust (CAT) in partnership with University of Fort Hare were technologies aimed at promoting CA within the province (Muzangwa *et al.*, 2021), as such;

experimental trials were developed to investigate the positive returns from a CA practice (i.e. the University of FortHare CA trial and Phandulwazi CA trial) (Figure 2.3). The adoption of CA remains low due to different limiting factors to its practice such as its failure to improve soil properties and yields with limited duration (short-term) (Nyambo *et al.*, 2022). Limited knowledge about the CA practice on farmers with disadvantaged educational background, lack of resources, poverty and different utilization of residues by small-scale farm producers contributes to improper implementation of CA principles.



Figure 2.3: Conservation agricultural trial at Phandulwazi experimental site

2.5.1 Effect of no/ minimum tillage system on soil physical properties & erosion

Minimum to no soil disturbance is an agronomic approach for sustainable crop cultivation (Figure 2.4). The idea was initiated back in 1940s by Edward H. Faulkner, but farmers started the practice after WWII after the development of effective chemical weed control (Derpsch, 1998). The adoption has significantly spread worldwide (Derpsch, 2010). No-tillage practice reduces soil erosion that is facilitated by conventional tillage in soils, particularly sandy soils on inclined surfaces. Additional benefits advances in NT comprise of enhanced soil permeability, moisture, SOM accumulation and nutrient distribution (Caires *et al.*, 2005). This method enhances the soil's biological variability and decrease the soil's susceptibility to erosive factors (FAO, 2021). Soils sequesters atmospheric

carbon when correctly managed, soils have the potential to reduce about 21% of carbon resulting from land practices such as tillage (Watson *et al.*, 2000).



Figure 2. 4: No-till vs tilled plots at Phandulwazi Conservation agricultural site

Numerous studies have reported benefits of NT contrasted with CT (Moraru and Rusu, 2013; Zuber *et al.*, 2015; Haruna *et al.*, 2018; Nyambo *et al.*, 2022; Gura *et al.*, 2022). An overview of recent research on various tillage systems and responses of various soil physical parameters, globally, is summarized on Table 2.1 below.

Table 2. 1: Effects of tillage on soil physical properties from various studies in literature

Tillage system	Soil type	Climatic condition	Effect on Soil	Study
Conventional and inversion tillage (C-IT), conventional and no-tillage (C-NT), organic and inversion tillage (O-IT), organic and reduced tillage (O-RT).	Calcareous Cambisol.	1050 mm rainfall per annum and 9.4°C temperature at average.	Tillage decreased BD and WHC compared to no/reduce-tillage.	(Oliveira <i>et al.</i> , 2024)
No-tillage (NT), disk-sweep (DS), plow-sweep (PS) and deep plow-sweep (DPS).	Fine silty, mixed, superactive, mesic Aridic Argiustoll soil (USDA).	Mean temperature of 10 °C and 460 mm of rainfall per annum at average.	No significant effects on BD and Infiltration, Tillage reduced AGS and PAW	(Klopp <i>et al.</i> , 2024)
Conventional (tillage), No-tillage, Integrated agroecosystem (livestock Grazing) and Natural ecosystem .		Semi-arid climate.	High AGS, WHC and PR on conservation agroecosystem (NT), BD and ϕ not significantly affected.	(Mamabolo <i>et al.</i> , 2024)
Conventional tillage (CT), reduced tillage (RT), and both (CRT).	Silt loam (Gee &Bauder, 1986).	9.5 °C temperature annual precipitation of 470 mm at average.	Reduced tillage increased BD. Ks increased in CT. NT reduced macroporosity and pore connectivity.	(Pöhlitz <i>et al.</i> , 2024)
Two levels of tillage(CT and NT).	Varies from silt to silty clay loam.	Annual precipitation values were 599, and 374 mm for the study seasons.	NT practice significantly increased SOM and BD but decreased Ks compared to CT.	(Saha <i>et al.</i> , 2024)

No-tillage (NT), subsoiling (ST), conventional tillage (CT), and NCS rotations.	Middle loam soil (FAO/UNESCO Soil Classification, 1993).	Semi-humid continental monsoon climate.	NCS rotation decreased BD and increased ϕ , soil macroaggregates content, nutrients accumulation and distribution.	(Zhang <i>et al.</i> , 2021)
Tillage practices: combined minimum tillage (MT) and conventional tillage (CT).	Sand=663.8 g.kg ⁻¹ , Silt=162.2 g.kg ⁻¹ , Clay=174.0 g.kg ⁻¹ (International Pipette Method (Piper, 1950).	Sub-tropical humid climate.	NT improved macro water stable aggregates, MWD, total ϕ and WHC.	(Kalita <i>et al.</i> , 2024)
Conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).	Deep clayey Vertisol (Isohyperthermic Typic Haplustert).	Hot sub-humid climate.	MWD, SOC and WSA were significantly higher in NT followed by RT and CT. NT had highest soil quality Index.	(Naorem <i>et al.</i> , 2023)
Plow tillage (PT), subsoiling tillage (ST), and rotary tillage (RT).	Udoll soil type (USDA).	Warm, temperate, semi-humid continental monsoon climate.	BD, PR and WHC reduced after tillage.	(Zhao <i>et al.</i> , 2022)
NT with straw cover and CT	Red soil type	Subtropical plateau monsoon climate.	NT increased soil moisture content and reduced BD in the topsoil compared with CT	(Bai <i>et al.</i> , 2022)

Ploughing (PL), minimum-tillage (MT), and no-tillage (NT)	Sandy loam (FAO Stagno Gleyic Luvisol)	Mean annual temperature was 9.6 °C and 10.1 °C during the growing seasons	NT increased BD, shear strength, soil moisture content and OM compared to ploughed soil.	(Alskaf <i>et al.</i> , 2021)
Conventional tillage (CT), minimum tillage (MT), and no-tillage (NT)	Loam textured soil	Temperate warm semi-arid climate	Reduced tillage and crop residue addition enhanced AGS by reducing PAD index significantly.	(Alinejadian-Bidabadi <i>et al.</i> , 2021)
Two levels of tillage: conventional tillage (CT) and no tillage (NT)	Sandy loam soils	Semi-arid climate	BD under NT was decreased, the total porosity and WHC under NT increased	(Bag <i>et al.</i> , 2020)

CT, conventional tillage; NT, no tillage; ST, subsoiling; NSC, rotations of no-tillage - subsoiling - conventional tillage; PAW, plant available water; WHC, water holding capacity; Ks, saturated hydraulic conductivity; AGS, soil aggregate stability; WSA, water stable aggregates; PR, penetration resistance; PAD, percentage of aggregate destruction; BD, bulk density; ϕ , porosity; SOM, soil organic matter; OM, organic matter.

2.5.2 Effect of Crop rotation on soil physical properties and erosion

Diversification of crop species to better soil quality, nutrient circulation and fight pests and diseases within a field is one sustainable approach to effective farming. This cropping type requires sequential cultivation of three crop species or more (Haruna and Nkongolo, 2019). Repeated cultivation of one plant species negatively impacts soil structural aggregation and moisture within the South African agricultural soils (Njaimwe, 2010). Farmers have noticed a beneficial approach in cultivating seasonal animal feed during spring instead of grain for the restoration and maintenance of productive soils. The practice of crop diversification is enhanced through amending with manure and incorporating various agronomic practices of sustainable farming (Gegner and Kuepper, 2004).

Proper adoption of a rotational cropping system improves soil structural properties, macro and microbial diversity and combat insect and pathogenetic threats (FAO, 2021). Crop rotations potentially decrease the rates of soil degradation by erosion. On regions with high vulnerability to degradation forces, agronomic approaches like minimum soil disturbance incorporated with certain crop species diversification lowers sediment detachment, translocation, deposition, and erosion (Unger and McCalla, 1980). When a forage crop decomposes naturally, it contributes to the formation of binding products that stick soil particles together eventually forming aggregates that are stable to erosivity (Jefferson *et al.*, 2016). Various crop rotation effects on soil properties are highlighted in Table 2.2 below.

Table 2. 2: Effects of crop rotation on soil physical properties from various studies in literature

Rotation	Soil type	Climatic condition	Effect on Soil	Study
Maize and soybean.	Waldron silt loam (UDSA).	Sub-humid climate.	OM increased/improved. pH reduced/dropped.	(Haruna and Nkongolo, 2019)
Maize-oat-wheat.	Arcadia soil form (Vertisol), Silty clay loam texture.	Sub-humid warm temperate	lower BD High MWD High FC, increase on soil structure and porosity.	(Njaimwe, 2010)
Maize-oat-wheat.	Shortlands soil form (Chromic Luvisol).	Sub-humid warm temperate.	No effect on FC, Higher aggregate stability (MWD).	(Njaimwe, 2010)
Maize-wheat-soybean.	Oakleaf soil form (Van Averbek and Marais, 1991), sandy clay loam texture (Nciizah and Wakindiki, 2014).	Sub-humid climate.	Affected crop biomass and carbon input.	(Muzangwa, 2016)
Maize-wheat-soybean.	Oakleaf form (Van Averbek and Marais, 1991), sandy loam texture (Muzangwa, 2016).	Semi-arid climate.	Increased biomass and carbon input and consequently POM and SOC.	(Muzangwa, 2016)
Sweet sorghum and grazing vetch.	Alluvial origin, Haplic Cambisol (IUSS	Semi-arid and relatively mild.	Increased ammonium and nitrate by 3.42% to 5.98%	(Malobane <i>et al.</i> , 2020)

Working Group WRB. 2006).				
Maize-oat- grazing vetch.	Oakleaf soil (Land Type Survey Staff 2001).	Semi-arid climate.	AGS was affected, enhanced by grazing vetch and inhibited by oats.	(Mupambwa and Wakindiki, 2012)
Black oat – maize intercropped with cowpea.	Acrisol (WRB).	Subtropical climate.	Increase macroaggregates	(Conceição <i>et al.</i> , 2013)
Maize-wheat-soybean.	Haplic Plinthosol (IUSS Working Group WRB, 2006).	Sub-humid climate.	No significant effects were observed	(Gura <i>et al.</i> , 2022)
Maize-oat- grazing vetch.	Alluvial origin, Haplic Cambisol (IUSS Working Group WRB 2006).	Semi-arid climate.	Increase soil fertility (P, Zn and mineral N) and yield.	(Dube <i>et al.</i> , 2013)
Maize-wheat-soybean.	Haplic Cambisol (IUSS working group WRB).	Semi-arid warm temperate climate.	Reduced BD and PR.	(Nebo <i>et al.</i> , 2020)
Maize-oat-maize.	Deep alluvial origin, Haplic Cambisol (IUSS working group WRB).	Semi-arid warm temperate climate.	High cumulative above ground biomass which positively correlated to C input.	(Nyambo <i>et al.</i> , 2022)
Maize–Oat–Maize.	Deep alluvial origin, Haplic Cambisol (IUSS working group WRB).	Semi-arid warm temperate climate.	Topsoil enhanced biomass input and MWD.	(Nyambo <i>et al.</i> , 2022)



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Corn-soybean-oat-wheat.	variation from silt to silty clay loam (USDA).	369, 599, and 374 mm, annual precipitation for 2020, 2021, and 2022.	crop rotation reduce BD and increase WAS	(Saha <i>et al.</i> , 2024)
Maize-wheat-green gram.	Sandy loam (Typic Haplustept).	Semi-arid climate.	Crop rotations effectively improved the soil's hydro-physical properties .	(Patra <i>et al.</i> , 2023)
wheat-pea.	Dooley sandy loam (fine loamy, mixed, frigid Typic Argiboroll).	Annual mean temperature and precipitation of 8 °C and 357 mm.	Crop rotation significantly affected various soil physical properties.	(Sainju <i>et al.</i> , 2022)

OM, organic matter; BD, bulk density; MWD, mean weight diameter; FC, field capacity (water); POM, particulate organic matter; SOC, soil organic carbon; PR, penetration resistance; C, carbon; WAS, wet aggregate stability.



2.5.3 Effect of crop residue on soil physical properties & erosion

Organic soil cover is the residual material retained on land following harvest (Figure 2.5), they encompass various plant parts that later decompose to OM (Murungu *et al.*, 2011). They can also be biodegradable leftovers from processing (process residues) and are useful as feed, amendments and nutrient suppliers to soils (Richards *et al.*, 1984). Adequate utilization of residues aid in soil hydraulic improvements, water supply and addresses erodibility & erosivity (Stinner *et al.*, 2008).

Agricultural practices that support organic soil cover contributes to potential returns in soil physical properties (Strauss *et al.*, 2021a). Whalen *et al.*, (2003) observed improvements in aggregate stability within residue retention practices on cultivated lands. The micro-pores and macro-pores are sustained by crop residues in contrast to the uncovered fields (Unger & Parker, 1976). The presence of sufficient crop rotation on the topsoil minimizes water evaporation (Parihar *et al.*, 2019) and reduce the effect of raindrops to disintegration of soil particles that ultimately leads to erosive degradation (Mhazo *et al.*, 2016). Shaver *et al.*, (2002) observed that cropping systems with extra crop residues decreased BD and increased total and effective porosities and AGS after 12 years of a NT practice. Gura and Mnkeni, (2019) reported no effect of crop diversification on AGS, yet residues showed an effective response to stability index (SI) within the surface soil. These SI responses were likewise presented by Denef *et al.*, (2022) from a 42-day lab study following addition of wheat residues.



Figure 2. 5: Crop residues on No-tillage practice at Phandulwazi CA trial

Soil cover shields the surface and protects soil particles from erosive forces (Durán *et al.*, 2007) and improves soil permeability as well as water percolation through the soil (Wainwright *et al.*, 2002). Therefore, infiltration can be increased, with reduced runoff through agronomic practices such as CA (Osman, 2012). The presence of these residues enhances soil health and structure as well as suppressing weed growth. All these factors contribute to soil sustainability. Table 2.3 presents various soil responses to crop residue management practices employed in different regions with various environmental conditions and agronomic practices.

Table 2. 3: Effects of crop residues on soil physical properties from various studies in literature

Residue management	Soil type	Climatic condition	Effect on Soil	Study
Distinct crop residues: Elbon rye, daikon radish, Austrian winter field peas and their mixture.	Marietta silt loam.	Humid subtropical climate.	BD reduced, pH increased, AGS improved. WSA under peas was significantly higher. The soil erodibility factor did not change significantly.	(Dai <i>et al.</i> , 2024)
Cotton stubble removal (Rm) and stubble return (Rt).	silty clay loam.	Temperate monsoon climate.	Micro-aggregates reduced in the topsoil.	(Zhang <i>et al.</i> , 2024)
Different levels of Crop cover: crimson clover, hairy vetch, winter peas, oats, winter wheat, triticale, flax and barley.	Cumberland silt loam.	Average annual precipitation were 1793 and 1509 mm in the two seasons.	High BD, non-capillary pores and air-filled pores on NC than crop cover.	(Lieskamp <i>et al.</i> , 2024)
Different crop cover: soybean (SB), sudan grass (SG), both (SB and SG), and no cover crop (CK).	Cumulic Haplustoll (USDA) (Soil Survey Staff, 2010).	Continental monsoon climate.	Crop cover improved soil physical properties and soybean residue incorporation significantly improved soil quality.	(Yang <i>et al.</i> , 2024)
Cover crops used: non-leguminous, broadleaf turnip and swede, (i.e., rutabaga).	Silty clay soil (PN-R-04032, 1998).	Humid continental (Dfb) climate.	Crop residues significantly improved wet aggregate stability. BD was lower in	(Domagata-Swiątkiewicz <i>et al.</i> , 2023)

Rice residue management options (0, 25 and 50%).	Well-drained sandy loam soil.	22 to 34°C maximum temperature and the minimum temperature from 10 to 27°C with 1796mm annual rainfall.	the soil under swede cover than in the control soil.	(Sarker <i>et al.</i> , 2022)
No-till farming, no burning and residue retention.		Warm sub-humid lowlands.	NT with greater crop cover reduces soil loss and improve soil hydrological properties without negatively affecting crop yield.	(Molla and Desta, 2022)
Two crop residue management practices: all stubble returned, and residues removed.	Udoll (USDA).	Warm, temperate, semi-humid continental monsoon climate.	Residue return was beneficial for WHC, BD and SOC.	(Zhao <i>et al.</i> , 2022)
Two crop residue managements: removed (REM) and retained (RET) residues.	Silty clay loam Mollisols.	Continental monsoon climate.	Residue retained plots registered a lower PR than residue removed plots on various tillage practices.	(Wang <i>et al.</i> , 2022)
Three residue management treatments: green cane harvesting, deeper Mollic Nitisol	Two types of soil: Mollic Cambisol and a deeper Mollic Nitisol	Humid subtropical climate.	Residue management practices had a higher effect on hydro-structural variables (shrinkage,	(Deeb <i>et al.</i> , 2021)

partial burning, and full burning.	(IUSS Working Group WRB, 2015).		specific volume, and swelling capacity) compared with fertilization.
Straw retained on residue retention plots and removed from the other plots.	Sandy loam (FAO Stagno Gleyic Luvisol).	Mean annual temperature was 9.6 °C and 10.1 °C during the growing seasons	Residue retention increased the average pore size. (Alskaf <i>et al.</i> , 2021)
Two levels of residues: maize residue at 5 t ha ⁻¹ (R+) and without residue (R0)).	Sandy loam soils.	Semi-arid climate	The Ks was significantly enhanced with residue retention, Root growth was improved under NT and crop residue mulching. BD reduced with mulch. (Bag <i>et al.</i> , 2020)

R+, residues retained; R-, residues removed; WHC, water holding capacity; WSA, water stable aggregates; Ks, saturated hydraulic conductivity; BD, bulk density; ϕ , porosity; SOC, soil organic carbon; OM, organic matter



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Soils respond to the practice of conservation agriculture in various ways as influenced by varying climatic conditions, regions, soil types and time. Although the practice is advocated as sustainable and beneficial in all regions, it should be studied for its best implementation to enable optimal productivity. Soil physical properties are interrelated; one affects the other and are both negatively and positively correlated. With an increasing and expected to increase population worldwide, agricultural systems have to advance to improved sustainable food production to control the pressure and maintain the productivity within arable lands (Page *et al.*, 2020). The available literature presents CA principles regarding soil re-integration as one of the essential sustainable measures, since conventional agricultural practices contribute to soil quality and productivity loss overtime.

Study gaps

The need for promotion and improved implementation of CA principles to maximize yields while sustaining the ecosystem is of paramount significance. Consequently, assessment of the effect of CA as a control to soil degradation and sustainable farming remains key. The Eastern Cape region only have short-term studies that might not fully capture the positive returns from the CA practice, yet imperative to better its adoption. The need therefore remains to assess the effects of CA after extended periods on soil physical properties and soil erosion by water. Research on the medium to long term benefits of CA practices within the haplic plinthosol is still limited, though appropriate.



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CHAPTER THREE

This chapter has been submitted for publication to the journal of soil and tillage research (currently under review).

Effect of conservation agriculture after a decade of tillage, crop rotation and crop residue management practices on selected soil physical properties in the sub-humid region of Eastern Cape, South Africa

Abstract

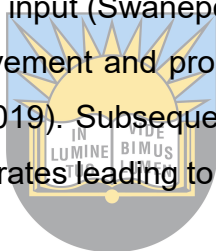
The conservation agricultural effects on soil physical properties are not immediately visible and are variable but might be observed in medium to long-term studies. This chapter aims in assessing the effect of conservation agricultural system after a decade of its implementation on selected soil physical properties in a sub-humid region of Eastern Cape, South Africa. The assessment was performed on a conservation agriculture (CA) field trial initiated in 2012, laid out in a randomized complete block design (RCBD) with split split-plot treatment structure consisting of 16 treatment combinations replicated into 3 blocks. The main plots, sub plots and sub-sub plots were allocated to tillage [no-tillage (NT) and conventional tillage (CT)], crop rotations [maize-fallow-maize (MFM); maize-fallow-soybean (MFS); maize-wheat-maize (MWM); maize-wheat-soybean (MWS)], and crop residue management system [residue retention (R+) and residue removal (R-)], respectively. Soil samples were collected from 0 – 10, 10 – 20 and 20 – 30 cm depths in the 2023/24 cropping season. The results showed that tillage practices had a significantly greater positive impact on bulk density (BD), porosity (ϕ) and aggregate stability (AGS)/ stability index (SI) compared to crop rotations and residue management. Soybean rotation treatments: MFS and MWS had 3.42% and 2.08% lower BD values compared with MFM and MWM, respectively. This is likely due to the quick decomposition of soybean residues, indicating potential improvement in soil health and soil quality with legume inclusion in rotations. Additionally, residue-retained plots had 24.24% higher gravimetric water content and 25.04% higher volumetric water content than residue-removed plots, due to the substantial amount of SOM returned by residue decomposition. There were no significant differences observed in Ks, which could be attributed to the

nature of the particle size distribution, as water moves more easily on sandy soils. These medium-term results present continual benefits from proper implementation of CA in sustainable farming and resource conservation.

Key words: Aggregate stability, bulk density, conservation agriculture, soil degradation.

3.1 Introduction

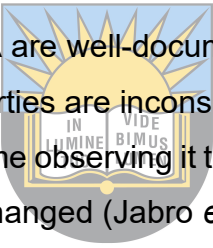
Conservation agriculture (CA) is centred on three linked components namely: reduced soil disturbance, crop diversification and residual surface cover. These principles can sustainably minimize soil physical degradation, improve surface permeability, and decrease erosion (Mtyobile *et al.*, 2020). Conservation agriculture is defined as one agronomic approach that sustainably enhances soil structural properties and improves agricultural productivity with minimal input (Swanepoel *et al.*, 2018). Additionally, CA has improved soil properties, water movement and promotes soil resilience against climate change (Giller *et al.*, 2009; FAO, 2019). Subsequently, CA has the potential to restore degraded lands and reduce erosion rates leading to improved soil health and productivity potential (Myeni *et al.*, 2023).



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Agronomic systems such as conventional tillage, monocultural production and removal of plant residues, commonly practiced under smallholder farming systems, cause soil degradation (Lal, 2015). Soil degradation includes processes such as erosion, compaction, acidification, soil organic matter and fertility depletion, biological decline, soil pollution, etc (Deborah *et al.*, 2008), which ultimately result in a significant decrease of soil quality. South African studies projected above 70% of the country to be impacted by different erosion intensities (Le Roux *et al.*, 2007; Van Antwerpen *et al.*, 2023). Soil loss within the South African region is annually rated at 12.3 t ha⁻¹ yr⁻¹ as predicted by Le Roux *et al.*, (2008), while soil formation rate is only 0.25 – 0.38 t ha⁻¹ yr⁻¹ (Matthee and Van Schalkwyk, 1984). Although soil erosion occurs naturally, it is exacerbated by unsustainable agricultural practices, especially in disadvantaged smallholder farms as influenced by poverty (Murungu, 2012). This necessitates sustainable and conservative agricultural production.

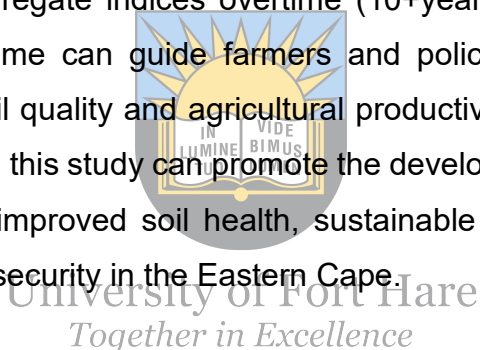
Soils in South Africa, particularly in the Eastern cape, are extremely fragile and vulnerable to degradation because of their mineralogy and fine sand fractions (Manyevere *et al.*, 2016). Their aggregate build-up mainly relies on soil organic matter (SOM) as they are generally low in clay minerals and oxide contents (Duiker *et al.*, 2003; Devine *et al.*, 2014). Consequently, the low SOM levels ($<10 \text{ g C kg}^{-1}$) of these soils increases their susceptibility to degradation and lowers their resilience (Meadows *et al.*, 2002; Mandiringana *et al.*, 2005). Sustainable agronomic management such as reduced soil disturbance assists in soil conservation, decreased erodibility and facilitates soil quality improvement (Zuber *et al.*, 2018). Resource conservation such as farmlands, soils and water sources are closely associated and corresponds with one another (Deborah *et al.*, 2008).



While the prospective gains from CA are well-documented, research findings on the role of CA on specific soil physical properties are inconsistent. Studies have reported varying effects on bulk density (BD), with some observing it to be lower (Mosaddeghi *et al.*, 2009), higher (Zuber *et al.*, 2015), and unchanged (Jabro *et al.*, 2016; Laghrour *et al.*, 2016) on NT in contrast to CT. Similar inconsistencies have been reported for penetration resistance, water infiltration, soil strength and aggregate stability. Kılıç *et al.*, (2004) reported contradictory variations in penetration resistance and bulk density in relation to moisture, sand, silt and clay contents on two soil types. Mtyobile *et al.*, (2020) observed higher porosity on CT with MFM and MWS, as well as NT with MWM and MWS within a haplic cambisol. Contradictions on soil BD expresses the need for more research, because for a given soil it reflects organic matter accumulation, aggregation, compaction, and it also affects water infiltration (Bhattacharyya *et al.*, 2006; Miriti *et al.*, 2013). The contradictory results are likely due to the influence of various factors on soil response to different agronomic practices. Climate, soil type/texture, SOM content and possibly the duration of CA implementation play a role in soil processes (Bescansa *et al.*, 2006; Mupambwa and Wakindiki, 2012). Time is particularly crucial for soil improvement through CA, as it's a long-term strategy. Unfortunately, most existing research focuses on

short-term effects. These short-term impacts may not fully capture the cumulative benefits of CA.

There is a scarcity of research on the medium to long term effect of CA on soil physical properties within the Eastern Cape. This medium-term study is crucial to evaluate the true potential of CA in restoring degraded soils and improving soil health and productivity in this region. This assessment aimed at filling the identified gap through evaluating the effect of mid-term conservation agronomic practices (no-tillage, crop rotations and crop residue retention) on selected soil physical properties in the sub-humid region of Eastern Cape, South Africa. It was hypothesised that no-tillage, rotational cropping, and crop residue retention potentially improves; (i) bulk density, particle density and porosity, (ii) gravimetric water content, volumetric water content and saturated hydraulic conductivity, and (iii) soil structural aggregate indices overtime (10+years). Knowledge of how soil properties respond over time can guide farmers and policymakers in optimizing CA strategies for long-term soil quality and agricultural productivity. Through assessing the timed effects on soil health, this study can promote the development of regionally tailored CA recommendations for improved soil health, sustainable agricultural practices, and ultimately, enhanced food security in the Eastern Cape.



3.2 Materials and Methods

3.2.1 Site description

This evaluation was performed at Phandulwazi Agricultural High School (32° 39' S and 26° 55' E) (Phandulwazi Jozini ecotope) (Figure 3.1), in the 2023/24 cropping seasons of an ongoing CA trial (Table 3.1). The experiment commenced from the 2012 summer growing season. Phandulwazi site is at an altitude of 735 meters above sea level (Geological Survey, 1984), it has sub-humid to humid climatic conditions and experiences 750 mm precipitation, annually (ARC-ISCW, 2016). The site has Avalon soil form according to the South African soils system of classification (Soil Classification Working Group, 2018), an Ultisol according to the USDA key to soil taxonomy (Soil Survey Staff, 2022), and a Haplic Plinthosol according to WRB (IUSS Working Group WRB, 2022). The

textural class for the soil is sandy loam (Appendix 10). Kikuyu grass was grown in the site preceding the initiation of the CA experimental trial.



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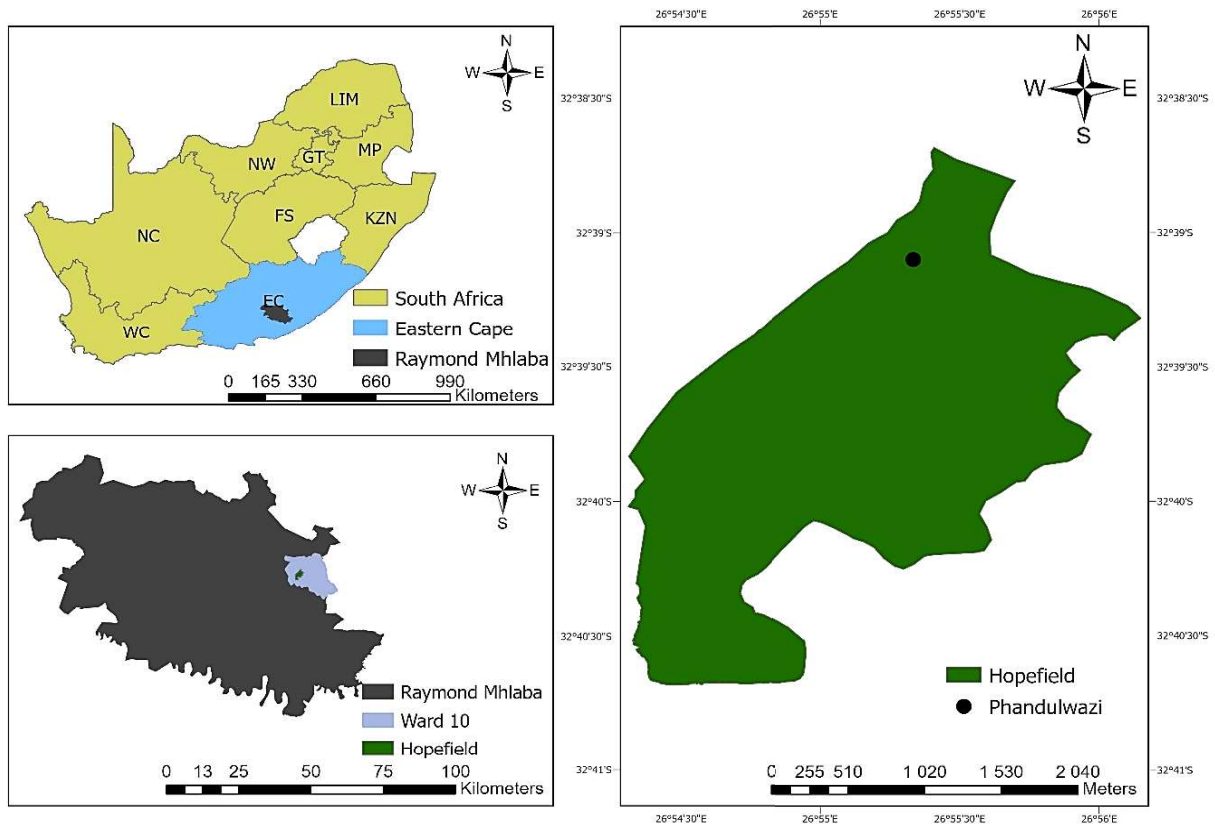


Figure 3. 1: A map presenting the position of the conservation agriculture trial in Phandulwazi, Eastern Cape

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3.2.2 Experimental design for CA trial

The experimental structure intended to contrast the interactive impacts of soil tillage, crop diversification and crop residual management practices. The experiment was designed following a split split-plot layout measuring 40 by 60 m in total area, with 16 treatment combinations of 6 by 5 m per plot, replicated into 3 blocks measuring 10 by 60 m (Figure 3.2). The main treatments were allocated to tillage (no-tillage (NT) and (conventional tillage (CT)), sub-treatments to crop rotations (maize-fallow-maize (MFM); maize-fallow-soybean (MFS); maize-wheat-maize (MWM) and maize-wheat-soybean (MWS)) and the sub sub-treatments to residue management (crop residues removal (R-) and crop residues retention (R+)).

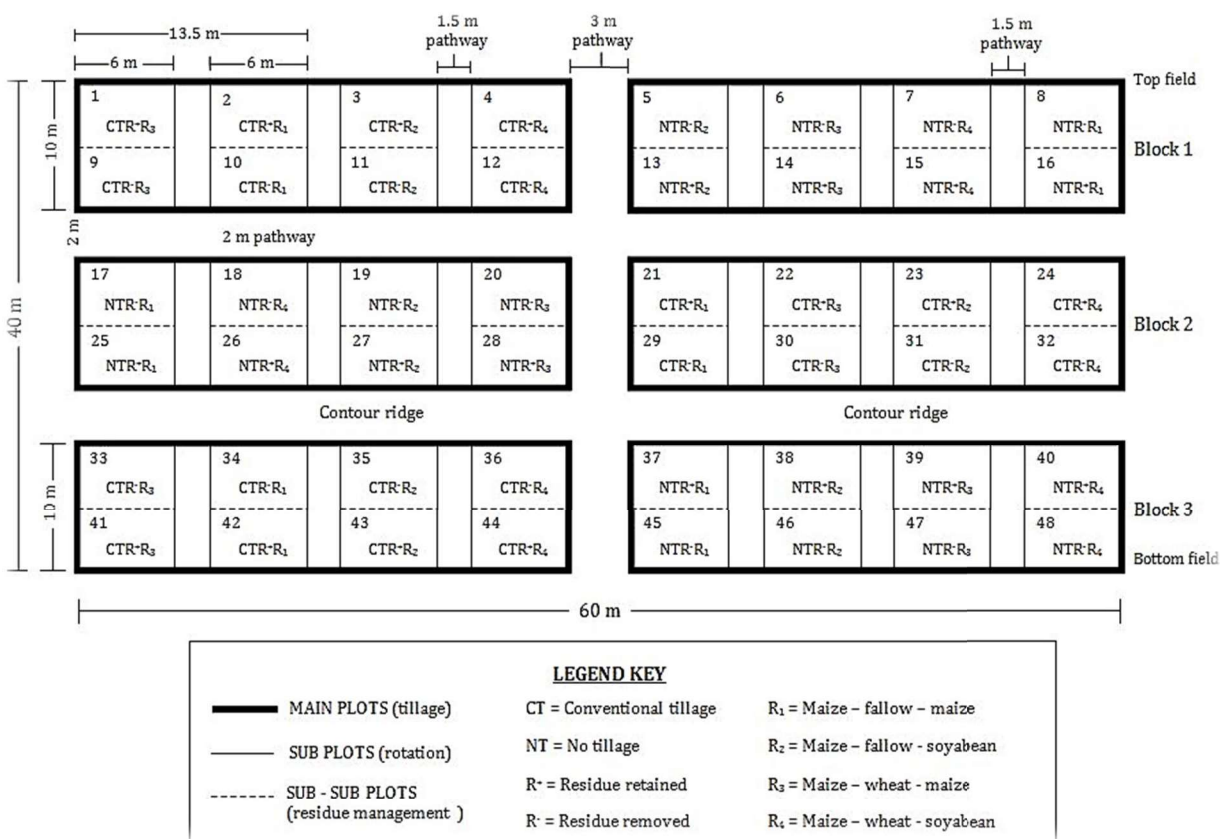


Figure 3. 2: Field layout of the conservation agriculture experimental site

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A summer season maize crop (*Zea mays*) variety (BG 5785BR) was sown at spacing of 40 cm within row and 100 cm between rows to obtain 25 000 plants ha⁻¹, suitable for drought stress in the Eastern Cape (Department of Agriculture, 2003). Soybean (PAN 5409RG) (*Glycine max*) was planted aiming roughly at 250 000 plants ha⁻¹. Rainfed spring wheat crop (SST 015) (*Triticum aestivum*) was first planted from the winter of 2013 at 100 kg ha⁻¹ seeding rate. For the summer maize, all plots were supplied with chemical amendment (fertilizer) at 90 kg N, 45 kg P and 60 kg K ha⁻¹ application rate targeting 5 tons ha⁻¹ output. A compound NPK fertilizer was supplied during cultivation (6.7% N; 10% P; 13.3% K + 0.5% Zn), and (60 kg) LAN (28% N) was applied 1.5 months post plantation through top-dressing. The experimental trial was sustained as rainfed, irrigation was done in cases of drought only to facilitate crop germination. Pertinent CT plots were tilled at +/- 20 cm depth with a mouldboard plough then disced (disc plough) to break larger peds, whereas other plots were not affected, particularly the NT treatment plots. Hand-held

hoes were used to prepare sowing parts of the NT treatments at about 10 cm depth. Crop residues were managed at harvest and incorporated in the soil or left on the soil surface for the R+ and removed for R-. Residues were left on the surface during harvest, incorporated in the soil during tillage of CT plots, and the remaining were retained on the surface. On the other hand, no-tilled plots had residues retained on the soil surface at all times. The agronomic practices were continuously repeated to date. Table 3.1 shows a summary of crops grown between the nineteenth and twenty third (2021/22 to 2023/24) growing cycles.

Table 3. 1: Crops cultivated in the nineteenth to twenty third seasons at Phandulwazi conservation agricultural site

Crop rotation	Season 19: summer (2021/22)	Season 20: winter 2022	Season 21: Summer 2022/23	Season 22: winter 2023	Season23: summer 2023/24
Maize-fallow-maize (MFM)	Maize	Fallow	Maize	Fallow	Maize
Maize-fallow-soybean (MFS)	Soybean	Fallow	Maize	Fallow	Soybean
Maize-wheat-maize (MWM)	Maize	wheat	Maize	wheat	Maize
Maize-wheat-soybean (MWS)	Soybean	wheat	Maize	wheat	Soybean

3.2.3 Soil sampling and analyses

Ethical clearance was granted for the study by the institution's inter-faculty research ethics committee (IFHREC) (Appendix 1). Soil sampling was performed post crop harvest, six months from tillage. A total of forty-eight samples were collected per block for the determination selected soil physical properties. Prior to sampling, the soil surface was cleared, and noticeable material were removed. Three subsamples were gathered at random from 0 – 10 cm, 10 – 20 cm and 20 – 30 cm soil depth form individual treatment plot using a 7 cm diameter bucket soil auger. These depths were selected because mechanical tillage loosens the topsoil (0 – 30 cm). The subsamples were merged forming a composite sample. Soil samples were transported to the soil storage for drying and storage, then later repacked and used for analysis.

Laboratory analysis

Soil texture was determined following the hydrometer method by Bouyoucos, (1936). Briefly, 100 g of soil were saturated with distilled water and a Calgon solution. The suspension was mixed and transferred into a graduated cylinder, thoroughly mixed and let to rest for 40s before collection of first readings and second readings collected after 2 hours using the hydrometer. Readings were corrected for temperature and soil texture was obtained through calculations.

Equation 1: Sand weight = Total sample weight – First reading value

Equation 2: %Sand = $\frac{\text{sand weight}}{\text{total sample weight}} * 100\%$

Equation 3: %Clay = $\frac{\text{second reading}}{\text{total sample weight}} * 100\%$

Equation 4: %Silt = 100% - (%sand + %clay)

The soil textural triangle was then used to identify the soil textural class.

Bulk density (BD) was obtained by the undisturbed soil core method as explained in Okalebo *et al.*, (2002). Briefly, A core ring of 10.7 by 3.8 cm height and radius, orderly, was used to sample the undisturbed soil. Masses were obtained by weighing after oven drying at 105°C. BD was then computed following equation 5.

Equation 5: Bulk density = $\frac{M_s}{V_t}$

Where: Ms is mass of dry soil and Vt is volume of soil.

The pycnometer method was used to determine soil particle density (P_s), all visible organic matter was removed from the sample. Briefly, P_s calculations were made from measured-sieved-oven dried soil samples that were mixed with distilled water and shaken to remove air in a volumetric flask, then weighed. Equation 6 was used for the calculation:

Equation 6: $P_s = \frac{M_s}{V_s}$

Where: Ms is mass of soil solids excluding pore spaces and Vs is their volume.

Gravimetric (θ_m) and volumetric (θ_v) water content were calculated from the weighed masses following their standard formulars (Osman, 2012) briefly, the samples were soaked in water overnight, covered with a water permeable cloth to allow full saturation,

the samples were then let to freely drain and weighed at field capacity (-33 Kpa), dried at 105°C for 24 hours to weigh at permanent wilting point (-1500 Kpa), presented by equation 7 and 8.

Equation 7: $\theta_m = \frac{M_w}{M_s}$

Equation 8: $\theta_v = \theta_m \frac{BD}{P_w}$

Where: θ_m is gravimetric water content ($g\ g^{-1}$), θ_v is volumetric water content, BD is bulk density ($g\ cm^{-3}$) and P_w is water density ($g\ cm^{-3}$).

Porosity (ϕ) was computed from BD and P_s (Osman, 2012), following equation 9.

Equation 9: $\phi = 1 - \frac{BD}{P_s}$

Where: P_s soil particle density ($g\ cm^{-3}$) and BD is soil bulk density ($g\ cm^{-3}$)

Soil aggregate stability (AGS) was determined using dry-sieving method described by Zhang *et al.*, (2012). briefly, each sample was air-dried, and dry-sieved with a 5 mm sieve. 150g of each sample was sieved by FTLHV-0200 filtra electromagnetic sieve shaker on a stack of sieves of 4 mm, 2 mm, 1 mm, 0,5 mm, and 0,25 mm sieve pore size. The sieves were shaken to separate the dry aggregates into different size classes. The weight of each fraction was then measured.

Wet-sieving method described by Vanek *et al.*, (2020) following a similar approach was employed for wet sieving, with stack of sieves moved into and out of water 50 times in 2 minutes. The weight of each fraction was then measured, and the data obtained was used to calculate the macro-aggregate stability indices following equation 10,11 and 12.

Equation 10: $MWD_{dry} = \sum_i^n W_i X_i$

Equation 11: $MWD_{wet} = \sum_i^n W_i X_i$

Equation 12: Stability index (SI) = $\frac{1}{MWD_{dry} - MWD_{wet}}$

Where: X_i is the mean diameter of the sieve size, and W_i is the ratio of stable aggregate weight to total weight for each size portion.

MWD_{dry} is the mean weigh diameter for dry sieving, MWD_{wet} is the mean weight diameter for wet sieving (Zhang et al., 2012; Vanek et al., 2020).

Field testing (in-situ)

Soil hydraulic conductivity (K_s) was measured using the SATURO dual head infiltrometer (DHI) from METER Group, (2017). The equipment was installed in-situ following the appropriate guide from the manufacture's manual, the equipment operates as a computerised single-ring infiltrometer having 2 levels of varying pressure head (low pressure head of 5 cm and 10 cm high pressure head). In the same way as pressure infiltrometers, it determines a 3-D percolation system in a soil. The test plot is dry at first and the ring is put on the surface to a 10 cm depth. The machine was then set following appropriate set-up for sandy dry soil and was allowed to automatically collect the readings that were later extracted from its hard drive (Angulo-Jaramillo *et al.*, 2016).

3.3 Statistical analysis

The data were tested for normality and subjected to analysis of variance (ANOVA) using JMP version 17.0 statistical software (SAS Institute, Inc., Cary, NC, USA). Student t-test was employed for mean comparisons. Significant variations were observed at three levels of statistical probability; $P < 0.05$, 0.01, and 0.001.

Excell was used for correlation analysis of all selected soil physical properties.



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3.4 Results

3.4.1 Effects of tillage, crop diversification and crop residue management on soil Bulk density, particle density and porosity

Treatment interactions had no significant effects on BD except for the three-way interaction between tillage × crop diversification × crop residue management ($P < 0.05$) at 0 – 10 cm soil depth (Appendix 2 & 7), and the two-way interaction between tillage × crop rotation at 10 – 20 ($P < 0.001$) and 20 – 30 cm ($P < 0.05$) depths (Table 3.2). Nevertheless, significant responses for BD ($P < 0.05$) were found on tillage and crop residue management main effects across all depths, except 20 – 30 cm depth (Table 3.3 & Appendix 2). Crop rotation showed significant effects on BD at the 0 – 10 cm ($P < 0.001$) and at 20 – 30 cm ($P < 0.05$) soil depths (Table 3.4). Bulk density was higher in CT plots under MFM and MFS with R-, compared to NT, MWS with R+ (Appendix 7). The least BD (1.4 g cm^{-3}) was observed under NT × MFS while the maximum (1.6 g cm^{-3}) was under CT × MFM (Table 3.2).

Particle density (P_s) had insignificant response ($P > 0.05$) to treatment interactions (Appendix 2). Nonetheless, tillage and crop residue management main effects were significant ($P < 0.05$) at 0 – 10 cm and 10 – 20 cm depths (Table 3.3 & 3.5). Similarly, crop rotation was significant ($P < 0.05$) only at 0 – 10 cm soil depth (Table 3.4). P_s was not highly variable as the measured samples were from the same field with similar soil texture, only OM influenced the P_s variability (Table 3.3 – 3.5). The interaction between tillage × crop diversification and crop diversification × crop residue management had significant effects ($P < 0.05$) on porosity across 0 – 30 cm and 10 – 20 cm soil depth, respectively (Table 3.2 and Appendix 2). Tillage consistently showed significant effects on soil porosity across all soil depths whereas crop diversification and crop residue management practices were significant only at 10 – 20 and 20 – 30 cm soil depths (Tables 3.3 – 3.5). The highest porosity (44.9%) was on the NT × MFS treatment combination (Table 3.2). Porosity improved with reduced soil disturbance and crop diversification, further illustrated by a positive correlation between BD and Porosity from 10 – 20 cm depth (Table 3.6).

3.4.2 Effects of tillage, crop diversification and crop residue management on soil gravimetric water content, volumetric water content and saturated hydraulic conductivity

All treatment interactions showed significant response ($P < 0.05$) on θ_m at 20 – 30 cm soil depth. The three-way interaction (tillage $\times$ crop diversification $\times$ crop residue management) had significant effects ($P < 0.05$) across 0 – 30 cm soil depth on θ_m and only at 10 – 20 cm depth on θ_v (Appendix 2). Two-way interaction (tillage $\times$ crop rotation) significantly affected θ_m ; θ_m and θ_v ; and θ_m at 0 – 10; 10 – 20; and 20 – 30 cm soil depths, respectively (Table 3.2). The interaction between crop diversification and crop residue management showed a strong positive significant effect ($P < 0.001$) on θ_m at 0 – 10 cm depth and on θ_v ($P < 0.01$) at 20 – 30 cm depth (Appendix 2). Tillage significantly affected ($P < 0.05$) both θ_m and θ_v at 0 – 10 and 10 – 20 cm depths (Table 3.3), NT had improved θ_m and θ_v whilst CT had reduced θ_m and θ_v . Crop rotation had significant effects ($P < 0.001$) across all three depths, while crop residue management showed significant effects at 0 – 10 cm ($P < 0.001$) and 20 – 30 cm ($P < 0.01$) soil depths (Table 3.3 – 3.5). Both θ_m and θ_v improved with CA implementation (Table 3.3 – 3.5), and θ_m increased with an increase in number of crops in rotation (Figure 3.4). The measured θ_m and θ_v explains the soil's potential in water (moisture) retention, and ultimately soluble nutrients distribution within CA versus CT practices. This is achieved through improved soil moisture by CA since soil water aids in nutrient distribution and accessibility by plants. There was no significant response in saturated hydraulic conductivity for all treatment interactions and main effects. However, CT treatment plots had relatively higher values of K_s (30.6 mm.h⁻¹) than NT (15.2 mm.h⁻¹) (Table 3.3).

3.4.3 Effects of tillage, crop diversification and residue management on soil structural aggregate indices

Soil structural properties (i.e. dry and wet mean weight diameter as well as soil stability index) had no significant responses except for the three-way interaction of tillage $\times$ crop diversification $\times$ crop residue management on MWD_{dry} ($P < 0.05$) at 20 – 30 cm depth

(Appendix 2). The two-way interaction between crop diversification and crop residue management showed significant effects ($P < 0.05$) on MWDwet and SI at the 10 – 20 cm depth, also on MWDdry and SI at 20 – 30 cm soil depth (Appendix 2). Tillage and crop rotation two-way interaction significantly affected MWDwet ($P < 0.05$) at 20 – 30 cm depth (Appendix 2). Tillage practice had significant ($P < 0.001$) effects on soil structural indices across the three depths studied (Table 3.3). Crop rotation significantly impacted MWDwet at all soil depths ($P < 0.05$), as well as SI and MWDdry at 20 – 30 cm soil depth (Table 3.4). Crop residue management resulted in varying significant responses ($P < 0.05$) for only MWDwet at 10 – 20 cm, MWDdry and SI at 10 – 20 cm, and only SI at 20 – 30 cm depth (Table 3.3 – 3.5). Soil structure improved with inclusion of legumes in rotation and reduced soil disturbance (i.e. MFM < MFS, MWM < MWS and CT < NT), (Table 3.3 & 3.4). CT plots had MWDwet less than 0.4, presenting very unstable aggregates compared to the partially stable CA plots with MWDwet greater than 0.4, in accordance with Le Bissonnais (1996).



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Table 3. 2: Interaction effects of tillage practices and crop rotation on soil physical properties at three different depths

Treatment	Soil physical properties									
	BD (g/cm ³)		θ_m (g/g)		θ_v (%)		ϕ (%)			
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
0-10cm depth										
MFm	1.54a	1.48bc	0.19e	0.22de	32.16d	32.06d	39.10d	41.96bc		
MFS	1.51ab	1.41d	0.24d	0.27c	33.77d	38.48cd	39.09d	44.93a		
MWM	1.52ab	1.42d	0.28c	0.34b	40.24cd	46.28bc	39.01d	43.29ab		
MWS	1.47c	1.42d	0.34b	0.42a	49.57ab	56.94a	40.76cd	42.74b		
Pvalue	0.11		0.03		0.62		0.02			
CV (%)	2.22		8.82		17.84		3.76			
10-20cm depth										
MFm	1.67a	1.54cd	0.20d	0.23cd	28.78f	36.27cde	33.07d	39.21ab		
MFS	1.62ab	1.52d	0.22cd	0.24c	33.95def	38.10bcd	34.54cd	41.44a		
MWM	1.54cd	1.58bc	0.23cd	0.28b	32.37ef	42.77b	38.15b	37.39b		
MWS	1.56bcd	1.56cd	0.28b	0.39a	39.92bc	59.51a	36.68bc	38.02b		
Pvalue	0.0004		0.002		0.0013		0.0003			
CV (%)	3.03		11.08		11.47		5.96			
20-30cm depth										
MFm	1.65a	1.57b	0.23d	0.25d	34.89d	40.31cd	34.18c	38.77a		
MFS	1.59b	1.56b	0.29c	0.24d	44.37c	39.49cd	36.02bc	38.42ab		
MWM	1.54b	1.57b	0.37a	0.38a	58.15ab	62.84a	38.63a	37.68ab		
MWS	1.56b	1.54b	0.36ab	0.34b	57.36ab	54.37b	38.63ab	40.16a		
Pvalue	0.042		0.0023		0.05		0.03			
CV (%)	3.04		10.64		10.92		5.62			

means in a column with different letters are significantly different; ns – not significant. BD = bulk density, θ_m = gravimetric water content, θ_v = volumetric water content, ϕ = porosity

Table 3. 3: The levels of selected soil physical properties at three different depths in response to no-tillage (NT) and conventional tillage (CT) treatments

Treatment	Soil physical properties							
	BD (g/cm ³)	Ps (g/cm ³)	θ _m (g/g)	θ _v (%)	φ (%)	K _s (mm/hr)	MWD _{dr} y	MWD _{wet} SI
0 – 10cm depth								
CT	1.51a	2.49b	0.26b	38.94b	39.49b	30.62	1.83b	0.39b
NT	1.43b	2.52a	0.31a	43.44a	43.24a	15.25	2.42a	0.47a
P value	<.0001	0.02	<.0001	0.04	<.0001	0.31	<.0001	<.0001
CV (%)	2.22	1.8	8.82	17.84	3.76	2.26	19.32	9.69
10 – 20cm depth								
CT	1.6a	2.55b	0.24b	33.76b	42.32a	-	1.99b	0.39b
NT	1.55b	2.46a	0.29a	44.16a	38.92b	-	2.45a	0.46a
P value	0.0009	<.0001	<.0001	<.0001	<.0001	-	<.0001	0.0001
CV (%)	3.03	1.91	11.08	11.47	5.96	-	16.1	13.25
20 – 30cm depth								
CT	1.58a	2.51	0.32	48.69	36.87b	-	2.00b	0.39b
NT	1.56a	2.55	0.31	49.25	38.74a	-	2.33a	0.47a
P value	0.05	0.05	0.24	0.72	0.0046	-	0.002	<.0001
CV (%)	3.04	2.28	10.64	10.92	5.62	-	15.90	12.03

means in a column with different letters are significantly different; ns = not significant. BD = bulk density, Ps = particle density, θ_m = gravimetric water content, θ_v = volumetric water content, φ = porosity, K_s = saturated hydraulic conductivity, MWD_{dry} = dry mean weight diameter, MWD_{wet} = wet mean weight diameter, SI = stability index.

Table 3. 4: The levels of selected soil physical properties at three different depths in response to crop rotation sequences

Treatment	Soil physical properties								
	BD (g/cm ³)	Ps (g/cm ³)	θ _m (g/g)	θ _v (%)	φ (%)	Ks (mm/hr)	MWDdry	MWDwet	SI
0-10cm depth									
MFM	1.51a	2.54a	0.21d	32.11c	40.53b	3.24	2.06	0.39b	0.63
MFS	1.46bc	2.52ab	0.26c	36.12c	42.02a	35.44	2.13	0.45a	0.69
MWM	1.47b	2.49bc	0.31b	43.26b	41.15ab	30.66	2.05	0.42a	0.66
MWS	1.44c	2.48c	0.38a	53.26a	41.75ab	22.39	2.26	0.46a	0.59
Pvalue	0.0002	0.01	<.0001	<.0001	0.11	0.45	0.57	0.0006	0.59
CV (%)	2.22	1.8	8.82	17.84	3.76	2.26	19.32	9.69	28.86
10-20cm depth									
MFM	1.61	2.51	0.22c	32.52c	36.47b	-	2.05b	0.37b	0.22
MFS	1.57	2.53	0.23bc	36.02bc	37.22b	-	2.26ab	0.46a	0.24
MWM	1.56	2.51	0.25b	37.57b	38.16ab	-	2.12b	0.43a	0.22
MWS	1.56	2.49	0.33a	49.71a	39.35a	-	2.43a	0.45a	0.25
Pvalue	0.09	0.28	<.0001	<.0001	0.015	-	0.06	0.0020	0.10
CV (%)	3.03	1.91	11.08	11.47	5.96	-	16.1	13.25	20.29
20-30cm depth									
MFM	1.61a	2.53ab	0.24d	37.59c	36.47b	-	1.72c	0.35b	0.76a
MFS	1.57ab	2.50b	0.27c	41.93c	37.22b	-	2.27b	0.43a	0.60bc
MWM	1.56b	2.52ab	0.38a	60.49a	38.16ab	-	2.10b	0.46a	0.69ab
MWS	1.55b	2.56a	0.35b	55.86b	39.35a	-	2.58a	0.45a	0.48b
Pvalue	0.04	0.12	<.0001	<.0001	0.015	-	<.0001	<.0001	0.0026
CV (%)	3.04	2.28	10.64	10.92	5.62	-	15.90	12.03	26.64

means in a column with different letters are significantly different; ns – not significant. BD = bulk density, Ps = particle density, θ_m = gravimetric water content, θ_v = volumetric water content, φ = porosity, Ks = saturated hydraulic conductivity, MWDdry = dry mean weight diameter, MWDwet = wet mean weight diameter, SI = stability index.

Table 3. 5: The levels of selected soil physical properties in response to crop residues retained (R+) and crop residues removed (R-) at three different depths

Treatment	Soil physical properties								
	BD (g/cm ³)	Ps (g/cm ³)	θm (g/g)	θv (%)	φ (%)	Ks (mm/hr)	MWDdry	MWDwet	SI
0-10cm depth									
R+	1.44b	2.47b	0.33a	47.08a	41.62	20.11	2.17	0.46a	0.65
R-	1.50a	2.55a	0.25b	35.29b	41.11	25.75	2.08	0.41b	0.64
Pvalue	<.0001	<.0001	<.0001	<.0001	0.26	0.71	0.45	0.002	ns
CV (%)	2.22	1.8	8.82	17.84	3.76	2.26	19.32	9.69	28.86
10-20cm depth									
R+	1.55b	2.48b	0.27	39.24	41.09a	-	2.32a	0.42	0.55b
R-	1.59a	2.54a	0.25	38.67	40.16b	-	2.11b	0.43	0.64a
Pvalue	0.0085	<.0001	0.13	0.66	0.016	-	0.04	0.44	0.014
CV (%)	3.03	1.91	11.08	11.47	5.96	-	16.1	13.25	20.29
20-30cm depth									
R+	1.54b	2.53	0.33a	51.59a	39.01a	-	2.25	0.43	0.58b
R-	1.61a	2.54	0.29b	46.35b	36.59b	-	2.08	0.42	0.68a
Pvalue	<.0001	0.58	0.002	0.002	0.0004	-	0.09	0.72	0.0437
CV (%)	3.04	2.28	10.64	10.92	5.62	-	15.90	12.03	26.64

means in a column with different letters are significantly different; ns – not significant. BD = bulk density, Ps = particle density, θ_m = gravimetric water content, θ_v = volumetric water content, φ = porosity, K_s = saturated hydraulic conductivity, MWDdry = dry mean weight diameter, MWDwet = wet mean weight diameter, SI = stability index.

Table 3. 6: Correlation analysis for the selected soil physical properties in the 0 – 10, 10 – 20, and 20 – 30 cm soil depths

	Bulk density	Mass wetness	Porosity %	MWDdry	MWDwet	Stability index (SI)
0 - 10 cm depth						
Bulk density	1					
Mass wetness	-0,63	1				
Porosity %	-0,84	0,26	1			
MWDdry	-0,77	0,33	0,88	1		
MWDwet	-0,77	0,67	0,64	0,6	1	
Stability index (SI)	0,58	-0,20	-0,77	-0,94	-0,44	1
10 – 20 cm depth						
Bulk density	1					
Mass wetness	-0,31	1				
Porosity %	0,29	-0,33	1			
MWDdry	-0,55	0,72	-0,49	1		
MWDwet	-0,42	0,45	-0,57	0,46	1	
Stability index (SI)	0,49	-0,51	0,42	-0,80	-0,38	1
20 - 30 cm depth						
Bulk density	1					
Mass wetness	-0,24	1				
Porosity %	0,46	0,29	1			
MWDdry	-0,47	0,26	-0,19	1		
MWDwet	-0,29	0,41	-0,42	0,46	1	
Stability index (SI)	0,55	-0,22	0,19	-0,97	-0,32	1

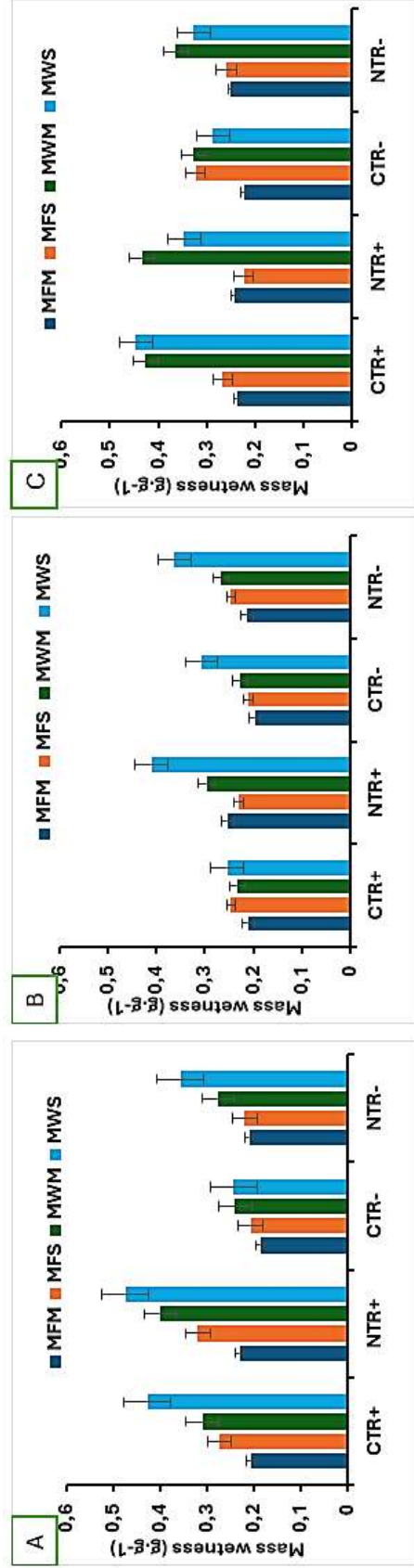


Figure 3. 3: Interactive effect of tillage, crop rotation, and crop residue management practices on mass wetness (Θ_m) at (a) 0 – 10 cm, (b) 10 – 20 cm and (c) 20 – 30 cm soil depth



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3.5. Discussion

Soil properties comprise of naturally inherent spatial variability from pedogenic factors but may be altered by tillage and/or other agronomic systems (Gülser *et al.*, 2016; Nebo *et al.*, 2020). The study aimed to investigate the medium-term implementation effect of conservation agronomic systems on particular soil physical parameters in the sub-humid region of the Eastern Cape province, South Africa. This is essential in management of the limited arable land, as it provides a detailed validation of the individual effect of conservative agricultural practices in sustaining the available resources and improving the previously degraded land. This can also be used in support of conservative management recommendations for smallholder farmers.

3.5.1 Bulk density, particle density and porosity

The lower BD observed under NT is due to improved soil structure and aggregation as a result of minimum soil disturbance on NT than soil loosening on CT. In contrast, tillage temporarily reduced BD by loosening the soil, creating additional soil porosity (Mosaddeghi *et al.*, 2009). This effect has been documented in several studies (Moraru and Rusu, 2013; Zuber *et al.*, 2015; Haruna *et al.*, 2018; Nyambo *et al.*, 2022). However, BD under CT later increases as the structure is disintegrated, the soil particles easily and quickly compact resulting in higher BD on CT compared to NT within one crop growing season. Tilled soil is generally unstable and consolidates over time, hence a significant increase in BD with reduced porosity on CT from time of tillage to full crop maturity, reflecting compaction on CT in contrast to reduced BD on CA overtime. Concisely, conversion from CT to NT initially result in increased soil BD up to reaching equilibrium; where the soil structure fully rebuilds, then proceeds reduction thereafter (Kinsella, 1995). Notably, the topsoil BD of NT (1.4 g.cm^{-3}) was lower than that measured in a short-term study (1.6 g.cm^{-3}) by Gura *et al.*, (2022) within the same experimental site, highlighting the significance of CA in soil structural development with time.

Low BD on MWS rotation compared to MFM was because of the improved aggregation that is influenced by the soybean crop in rotation, these observations were minimal on the short term, with high visibility on the medium-term (+ten years) CA practice. Residue retention increases SOM accumulation in the topsoil leading to improved BD and aggregation (Mupangwa *et al.*, 2011). BD and *Ps* improvements on the crop residue effect, might be due to the longer application of CA in this study as

contradictory results were observed on a short-term duration experiment by Gura *et al.*, (2022) where non-significant effect on BD and AGS on the crop residue retention treatments were reported. The observed BD values are however in the tolerable range for a sandy loam soil, hence favourable for crop's roots (Gura and Mnkeni, 2019).

Soil particle distribution did not differ as it develops from the parent material, and it is not altered by agronomic practices but influenced in terms of pedogenesis and age (Xinwei *et al.*, 2023). This explains the less affected particle density from this study. OM however, influenced the insignificant *Ps* variations amongst different treatment plots with its finer particles. Improvements in soil porosity are consistent with numerous long-term CA studies (Stone and Silveira, 2001; Sasal *et al.*, 2006; Tavares and Tessier, 2009; Pires *et al.*, 2017; Borges *et al.*, 2018) as porosity improves with aggregation/ structural build-up that is influenced by CA. Hypothesis one was therefore accepted, conservation agricultural system of no-tillage, crop diversification and crop residue retention practices does improve soil bulk density, particle density and porosity overtime.

3.5.2 Soil gravimetric, volumetric water content and saturated hydraulic conductivity

The significant responses observed on all selected parameters as influenced by CA at the topsoil except for saturated hydraulic conductivity (*K_s*) (Table 3.3 – 3.5), could be attributed to the nature of the particle size distribution as water moves rapidly on sandy soils. Contradictory trends on *K_s* with CA have long been explained in research (Zhang *et al.*, 2007; Hu *et al.*, 2009; Medina-Sauza *et al.*, 2019; Nebo *et al.*, 2020). The observed *K_s* however falls within the acceptable range (10^{-4} to 10^{-7} m.s⁻¹) (Topp *et al.*, 1997) for agricultural soils.

Short-term research by Gura *et al.*, (2022) showed crop rotations as less effective on soil indices compared to tillage and residue management during the first few years (after 4 seasons), because of the short period since the adoption of CA. Crop rotations require a prolonged period to significantly affect soil properties from different rooting systems of diversified crops (that facilitate various processes) and enhanced surface cover/ returned biomass. This study however found significant response to crop rotation effect as θ_m and θ_v increased significantly, reflecting improvements under MWM and MWS rotations (Table 3.4 & 3.2), this could be caused by the accumulated high above ground biomass (AGB) returned from the continued cultivation, which

resulted in high SOM accumulation and enhanced soil hydraulic properties (Nunes *et al.*, 2020).

Increase in θ_m and θ_v was mostly ascribed to NT coupled with crop rotation sequences (MWM and MWS) (Table 3.2), because of enhanced SOM (reported on a separate ongoing study) and hence improved soil water holding capacity. Pote *et al.*, (1999) reported surface residue to increase infiltration by 25 to 50% under a NT, this is coherent with the θ_m and θ_v response to crop residue effect of this study as their mean values increased with residue retention, representing a strong significance of mulch/crop cover to soil hydrological properties. The second hypothesis was accepted; no-tillage system, crop rotation and crop residue retention improve the soil's hydraulic properties such as gravimetric and volumetric water contents, however with the exception of saturated hydraulic conductivity.

3.5.3 Soil structural aggregate indices (MWDdry, MWDwet and SI)

Better soil aggregate stability (AGS) found on NT plots with crop rotation sequences employed (Table 3.3 & 3.4), was because soil aggregation is improved by reduced soil disruption and tillage frequency as also observed by Nielsen and Calderon, (2011). Gura *et al.*, (2022) and Malobane *et al.*, (2019) presented similar observations from short-term studies suggesting that a higher AGS resulted from the fallow practices employed, improved AGS in routinely cultivated treatments than fallow was reported from studies by Pikul *et al.*, (2006) and Blair *et al.*, (2006). Varying effect responses are expected because of factors such as the duration and type of the fallow, tillage practice and weed control (Nielsen and Calderon, 2011; Malobane *et al.*, 2019; Gura *et al.*, 2022). Increase in MWD (MWDdry & MWDwet), and low BD under NT confirms the positive returns of reduced tillage under CA in improving soil aggregation while reducing compaction. These observations have also been reported in several studies where aggregation was improved by minimum soil disturbance (Mosaddeghi *et al.*, 2009; Li *et al.*, 2019; Song *et al.*, 2019; Rocha *et al.*, 2020). Diversity in macro and microbial biota influenced by CA overtime, likewise, contribute to improved soil structural indices through facilitated decomposition, soil mixing with OM, and water channels construction by soil macro-organisms (nematodes). These enhance various processes of water infiltration, percolation and retention within the soil, thereby improving soil quality.

Treatments with soybean rotation (MFS and MWS) had significant greater effects on AGS than MFM and MWM (Table 3.4). This is likely due to the rapid decomposition of soybean residues, which results in higher OM content than wheat or maize residues. Soybean residues have a lower C:N ratio, facilitating faster breakdown (Chatterjee *et al.*, 2016; Zheng *et al.*, 2023). These responses validate the effectiveness of conservation agricultural practices and crop rotation overtime as CA requires time to register significant effects (Nyambo *et al.*, 2020). A meta-analysis by Zheng *et al.*, (2023) presented that crop rotation enhanced macro-aggregate size (> 0.25 mm), aggregate stability, and organic carbon contents from the third crop cycle or beyond, and 4+ crop rotation length. The improvements further assure high soil productivity potential for current and future production as they denote a good soil health. High MWD (both dry and wet sieving) in the residue retained treatments can possibly be caused by the topsoil build-up of SOM over time as SOM is crucial in the development and maintenance of soil aggregates (Mupangwa *et al.*, 2011). Maintenance of crop residues enhance soil quality as their decomposition releases a volume of nutrients to the soil, leading to conservable soil nutrition for a prolonged duration (Cherubin *et al.*, 2021), while crop residue removal affects aggregate stability by inducing soils' susceptibility to surface sealing and crusting (Blanco-Canqui and Lal, 2009). Hypothesis three was also accepted with observed improvements in soil structural aggregation (MWD_{dry} and MWD_{wet}) under CA practice overtime.

This study correspondingly found tillage system as the dominating agronomic practice affecting soil physical properties overtime, with CT being disruptive in relation to NT. Crop diversification and crop residue management also showed a strong significant effect to soil properties in the medium term, such observations were less visible in the short-term. High positive correlation between BD and SI; MWD and ϕ (Table 3.6) reflects a linked relationship as soil structural indices influence one another; a drop in BD is associated with improved hydraulic conductivity, soil aggregation and porosity with reduced compaction.

3.6 Conclusion

This study confirms that CA is an effective approach for mitigating soil physical degradation by enhancing specific soil physical properties like AGS, BD, and ϕ .

Furthermore, incorporating soybean into crop rotations and retaining crop residues significantly promotes soil health and fertility. These practices contribute to Sustainable Development Goals (SGD) 13 and 15 by limiting climate change and conserving life on land. Moreover, this study acknowledges that the timing of soil sampling can influence the results. To fully assess the efficacy of these treatments, it is strongly suggested to conduct long-term evaluations (>30 years), as time is a critical factor in soil reintegration via conservation agricultural practice.



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CHAPTER FOUR

Effect of conservation agriculture after a decade of tillage, crop rotation and crop residue management practices on runoff and soil loss in the sub-humid region of Eastern Cape, South Africa

Abstract

Soil erosion by water is strongly influenced by agronomic management practices within the agricultural arable land. Conservation agriculture (CA) can reduce soil loss through erosion by minimizing runoff. This study assessed the effects of tillage, crop diversification and crop residues management practices after a decade of CA on runoff and soil loss. The experiment was structured in a split split-plot lay out with 16 treatment combinations in 3 imitated blocks. The main treatments, sub treatments and sub-sub treatments were allocated to tillage, crop rotations, and crop residue management system, orderly. The rainfall simulator was used to generate a standardized rain-shower on a plot with standard surface area, the amount of runoff was determined by measurements, and sediments washed were obtained through drying and weighing. Results showed that NT₀ had 40% and 2.25% reduced soil loss and runoff compared to CT, respectively. In terms of crop rotation, the highest runoff and soil loss were observed under MFM and lowest under MWS. Likewise, Residue retention reduced soil loss by 22% and runoff by 4.38%. Low soil loss and runoff were attributed to low soil compaction, improved porosity, and better soil structure and aggregation. Runoff and soil loss were correlated with other physical properties while pedo-transfer functions to predict soil loss and runoff were developed using multiple linear regression. Furthermore, soil loss could be predicted from bulk density and mass wetness and runoff was estimated using bulk density and porosity on a developed model using multiple linear regression. The need for further model evaluation and validation remains crucial. This research can contribute to the development of regionally tailored CA recommendations for maintaining soil quality, and ultimately, reducing soil degradation while enhancing agricultural productivity.

Key words: Bulk density, conservation agriculture, soil degradation, soil erosion, mass wetness.

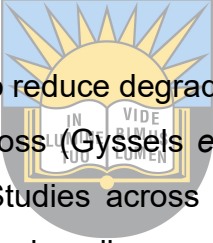
4.1 Introduction

Soil erosion by water is a challenge experienced worldwide, affecting the land and water resource management (Laker, 2004; Paterson *et al.*, 2013). It includes the degradation of productive surface soil leading to decreased agricultural productivity, and various off-site effects such as high translocation/ deposition to low surfaces and rivers (Flügel *et al.*, 2003). Borrelli *et al.*, (2017) predicted a mean of 2.5% (35.9 billion t year⁻¹) annual increase in global soil erosion, with 17 billion t year⁻¹ resulting from agricultural croplands. Highly erodible soils are vulnerable and worsen the chances of degradation, this is true to the fragile South African soils with low resilience especially those of the Eastern Cape province with low organic matter (OM) content (<10 g C/kg) which exacerbate their susceptibility to erosion (Meadows and Hoffman, 2002; Mandiringana *et al.*, 2005; Manyevere *et al.*, 2016; Njaimwe *et al.*, 2018).

Estimations by Le Roux, (2011) has shown annual rates of soil loss in SA to be 12.6 t ha⁻¹ yr⁻¹, as contrasted 0.25 - 0.38 t ha⁻¹ yr⁻¹ of soil development (Matthee and Van Schalkwyk, 1984). Although wind erosion accounts for 25% of SA soils susceptibility (Hoffman and Todd, 2000), erosion by water remains predominant as a cause of degradation in SA (Le Roux, 2011). Considering gully erosion, the Northern Cape and Eastern Cape Provinces are highly impacted, the Eastern Cape is estimated at about 6 188 581 km² of land to be affected by sheet-rill erosion and is the most affected province in all of SA (Le Roux, 2011). A great proportion of land within the province is affected by varying soil erosive forces (Le Roux *et al.*, 2008), this has been identified because of the thin and susceptible Eastern Cape soils (Fox and Rowntree, 2001). Conferring to Le Roux *et al.*, (2008), water erosion occurs mostly as sheet erosion through rain-splash and rill, or gully erosion are influenced by server degradation, water pathways/ newly constructed rivers and changes in rainfall patterns (i.e. duration and intensity). Sheet and rill erosions are generally not easily detectable as gullies; conversely, they are chief contributors to loss of productive soils of the surface layer in all of South Africa.

Poor agronomic management systems such as conventional tillage, mono cropping, and residue extraction increase the risk of soil loss through erosion (Lal, 2015). The conventional ploughing approach encompasses soil disturbance with crop material

removal, leaving the surface bare, result in reduced SOM on many South African fields. This decline in SOM relates to enhanced degradation and erodibility (Laker, 2004). Soil turnover through ploughing affects organic crop material, decrease carbon-stabilization, impend microbial decomposition, ultimately leading to green-house gas emissions (Dendooven *et al.*, 2012). Soil loss from agricultural fields is observed through decreased productivity potentials, reduced moisture and degraded drainage channels (Chivenge *et al.*, 2007). Literature projects tillage associated erosion as the main eroding factor in arable lands, exceeding water and wind related erosions from numerous fields, globally (Moraru and Rusu, 2013). Introduction of conservative measures to mitigate soil erosion and degradation have a significant potential in lowering the rates of soil loss and surface runoff (Haruna and Nkongolo, 2019). Conservation agriculture is progressively being indorsed as a sustainable, climate-smart approach that aid in regulation of soil degradation processes, promote water conservation and mitigates against climate change (Muzangwa *et al.*, 2021).



Research has shown plant cover to reduce degradation by acting as physical barriers to lessen surface runoff and soil loss (Gyssels *et al.*, 2005; De Baets *et al.*, 2007; Zuazo and Pleguezuelo, 2008). Studies across South Africa, even on very steep slopes, concluded that proper organic soil cover shields the surface during intense erosive precipitations (Smith *et al.*, 2000; Le Roux *et al.*, 2008). Whalen *et al.*, (2003) explained that continuous restoration of residues in repeatedly cultivated fields result to increased AGS and soil hydrology. Unger & Parker, (1976) observed the sealing of soil micro-pores and macro-pores being greatly lowered with residue retention. Thierfelder and Wall, (2012) established a greater cumulative soil erosion from CT treated fields compared to CA fields, South African modeling studies in field water balance showed a reduction under NT systems in surface runoff compared to CT (Mupangwa and Jewitt, 2011).

Provincial government attempts to introduce (CA) in the Eastern Cape have had limited success in general. It is therefore necessary to gain knowledge about the long-term effects of CA to make sound recommendations on the regulatory approach. Studies have not been systematic in researching the topic, with the exception of Le Roux, (2011) and Paterson *et al.*, (2013), who focused on the causes of erosion and how they affect agricultural production. The need for further research remains, mainly

on how conservation practices regulate soil loss and run-off. Establishment of control approaches to soil erosion is crucial (FAO, 2019). Hence the medium to long-term experiment is suitable for this objective. This study focuses on the effects of tillage, crop rotation and crop residue management practices after a decade of CA implementation on soil loss and runoff. It was hypothesized that proper implementation of conservation agricultural practices significantly reduces; (i) soil loss and (ii) runoff. Insight of how soil erosion can be controlled through sustainable agriculture can help guide farmers and policymakers in optimizing CA strategies for long-term soil management. By evaluating the medium to long-term impact on soil conservation, this research can add to the advancement of regionally tailored CA recommendations for maintained soil quality, and ultimately, reduced soil degradation with enhanced agricultural productivity in the Eastern Cape. This can also be used in support of conservative management recommendations for smallholder farmers.

4.2 Materials and methods

4.2.1 Site description

The simulation was performed on the same CA trial outlined in chapter 3.

4.2.2 Soil physical properties

The selected soil physical properties (BD, θ_m , ϕ , K_s , MWDdry, MWDwet) were studied and presented on chapter 3. The soil physical properties were subjected to principal component analysis (PCA) with soil loss and runoff. The soil loss and runoff prediction equations were developed from correlations between the available data for soil physical properties and measured soil loss and runoff from rainfall simulations using a stepwise approach multiple linear regression analysis.

4.2.4 Soil loss and run-off

A standardized rain-shower was generated by the rainfall simulator on a plot with standard surface area to measure runoff and soil loss in-situ (Figure 4.1), the field has flat - gentle slopes of 0 – 5 %. The plot area before sampling was wetted using the soil-wetting jar. Sample materials were collected in the 2-litre plastic sample box. The plastic sample box was used for the storage and transportation of the sample material (runoff sediments).



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Installation of rainfall simulator (M-0906E) in the plot.

The ground frame was installed using four nails, followed by the installation of the flexible support on the ground frame using the two levels and four knobs to level the support. The aeration pipe was closed with a plug, the sprinkler was then placed upside down on the support to fill the sprinkler with water from the water storage tank. The sprinkler was then turned around to its sprinkling position on the support. The rainfall intensity (6 mm/min) was adjusted using the aeration pipe; the shower of 375 ml.min⁻¹ at 20°C and 9 cm height for accurate rainfall simulation was used, and the simulation was carried out for 3 minutes (180 seconds). The distance between the reservoir and the upper side of the aeration pipe was set to obtain constant pressure for the rainfall intensity. Water level in the reservoir was carefully noted.

The simulation was started by removing the plug from the aeration pipe while starting the stopwatch. The drops released by the capillaries were similarly and randomly dispersed over the test plot. After three minutes, the simulation was stopped by placing the plug on the aeration pipe. The water level in the reservoir was noted. Sediments in the directing tray were added to the sample collection box using a wiper. All the material collected in the sample collection box were in one container, then transported to the laboratory, where the amounts of runoff was measured, and the deposited sediments were determined through drying and weighing.

The runoff sample sediments were filtered with the aid of Whatman filter paper to separate soil solids from the liquid sample. The sediments were oven dried for 24 hours at 105 °C to determine the weight of the soil loss at each sample (Figure 4.2) (Eijkelkamp; soil and water, rainfall simulator operating instructions manual, 2018).

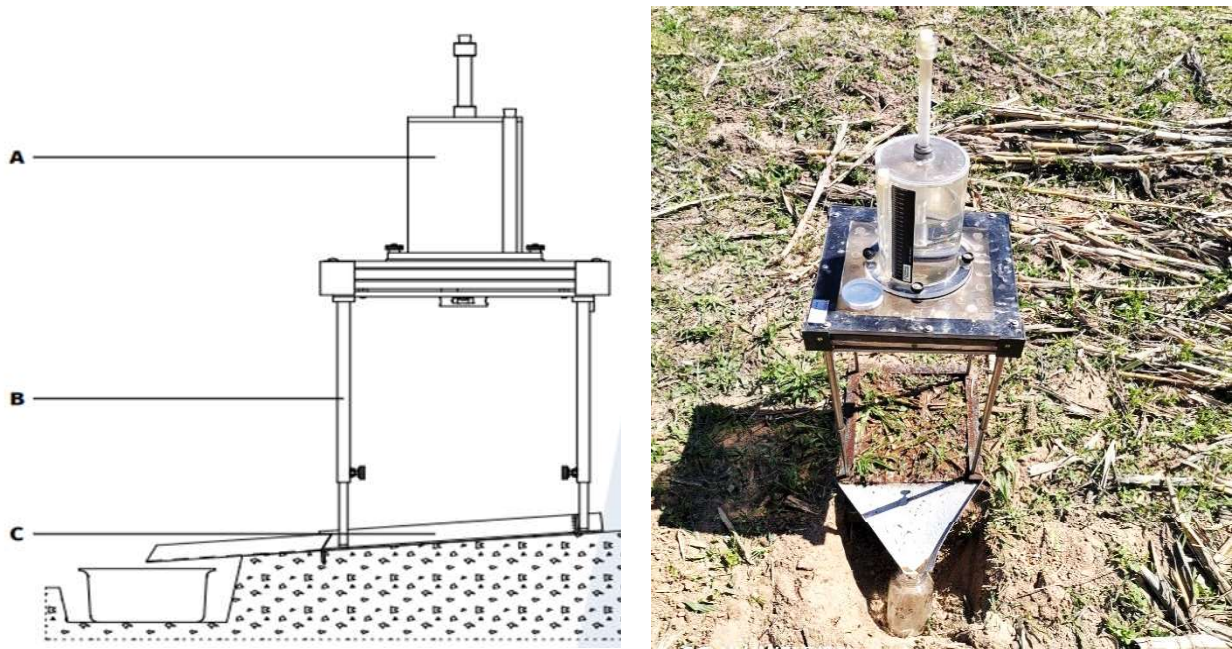


Figure 4. 1: The rainfall simulator (M-0906E) (mini rainfall simulator)



Figure 4. 2: Runoff sediments filtration (A), and sediment oven-drying at the laboratory (B)

Calculations

Soil loss was weighed from the dried runoff sediments, the masses in grams (g) were converted to soil loss per test plot (g/m^2), following equation 4.1.

Equation 4.1:
$$\text{Soil loss (g/m}^2\text{)} = \frac{\text{weighed sediment mass}}{\text{surface area of test plot}}$$

Further conversion to soil loss in tones per hector were performed by dividing by 100.

Runoff in millilitres per second (ml/s) was obtained by measuring the cumulative runoff collected after the simulation, following equation 4.2.

Equation 4.2: $\text{Runoff (ml/s)} = \frac{\text{measured runoff (ml)}}{\text{simulation time (s)}}$

Runoff coefficient was calculated from the total water used during the simulation and the measured cumulative runoff, following equation 4.3.

Equation 4.3: $\text{Runoff coefficient (\%)} = \frac{\text{total water applied}}{\text{measured runoff}} * 100$

4.3 Statistical analyses

The data were tested for normality and subjected to variance analysis (ANOVA) using JMP version 17.0 statistical software (SAS Institute, Inc., Cary, NC, USA). Comparison of means was carried out by Student t-tests. Significant differences were identified at three probability levels; $P < 0.05$, 0.01 and 0.001 .

JMP multivariate methods were employed for the development of principal component analysis (PCA) to correlate regressions between bulk density, mass wetness, saturated hydraulic conductivity, porosity, aggregate stability as well as soil loss and runoff. Only principal components with eigen-value >1 and soil physical properties with a loading matrix >0.6 were retained (Appendix 5).

Excell was used for a stepwise regression analysis, multiple linear regression with soil loss as the dependant variable, mass wetness and bulk density as the independent variables was performed to develop a soil loss prediction model. Likewise, runoff as the dependant variable as well as porosity and bulk density as independent variables were used to develop a runoff prediction model. Pearson correlations were used.

4.4 Results

4.4.1 Selected soil physical properties

The topsoil selected soil physical properties studied on chapter 3 showed significant effect responses ($P < 0.05$) to tillage, crop rotation and crop residue management main effects, with interactions (two-way interaction and three-way interaction) showing minimal effective responses, hence emphases were mostly based on main effects. The topsoil physical properties were sampled at 0 – 10 cm depth and studied as presented in table 4.1 below.

Table 4. 1: The levels of selected soil physical properties at 0 – 10 cm depth in response to tillage, crop rotation and crop residue management practices

Treatment	Soil physical properties					
	BD (g/cm ³)	θ_m (g/g)	ϕ (%)	Ks (mm/hr)	MWDdry	MWDwet
Tillage						
CT	1.51a	0.26b	39.49b	30.62	1.83b	0.39b
NT	1.43b	0.31a	43.24a	15.25	2.42a	0.47a
P value	<.0001	<.0001	<.0001	ns	<.0001	<.0001
CV (%)	2.22	8.82	3.76	2.26	19.32	9.69
Crop rotation						
MFM	1.51a	0.21d	40.53b	3.24	2.06	0.39b
MFS	1.46bc	0.26c	42.02a	35.44	2.13	0.45a
MWM	1.47b	0.31b	41.15ab	30.66	2.05	0.42a
MWS	1.44c	0.38a	41.75ab	22.39	2.26	0.46a
P value	0.0002	<.0001	ns	ns	ns	0.0006
CV (%)	2.22	8.82	3.76	2.26	19.32	9.69
Crop residue						
R+	1.44b	0.33a	41.62	20.11	2.17	0.46a
R-	1.50a	0.25b	41.11	25.75	2.08	0.41b
P value	<.0001	<.0001	ns	ns	ns	0.002
CV (%)	2.22	8.82	3.76	2.26	19.32	9.69

ns, not significant; BD, bulk density; θ_m , mass wetness; ϕ , porosity; Ks, saturated hydraulic conductivity, MWDdry, dry mean weight diameter; MWDwet, wet mean weight diameter.

4.4.2 Effect of tillage, crop rotation and crop residue management on soil loss and runoff

Main effects showed a dominant effect response over all treatment interactions (Table 4.2). The two-way interaction between tillage $\times$ crop residue management practices had a significant effect ($P < 0.05$) on soil loss and runoff coefficient. The crop diversification $\times$ crop residue management two-way interaction also had an effective response on soil loss only (Table 4.2). Tillage, crop diversification and crop residue management main effects significantly influenced soil loss and runoff coefficient, runoff was only affected by crop residues (Table 4.2). Soil loss was notably reduced in crop diversification combined with retention of residues (Figure 4.3). The soil loss was higher under MFM and lower under MWS for all tillage and residue management treatments (Figure 4.3). For each rotation, CT had higher soil loss compared to NT. Conventionally tilled plots with residues removed had high soil loss (0.32 t/ha) compared to conservation/ no-tilled plots with residues retained (0.18 t/ha) (Appendix 4). Lastly, soil loss was higher under residue removed treatment for each combination of tillage with crop diversification treatments.

Surface runoff was not highly significant, yet variations were observed with reduced water runoff in plots with full CA implementation (Figure 4.4). Conventional treatment (CTR-) had high surface runoff (3.24 ml/s) compared to conservation treated plots (NTR+) (3.03 ml/s) in conventionally tilled plots (Appendix 4). MWS had lower runoff compared to MFM and higher under residue removed compared to residues retained. However, in no-till plots with residues retained; the effect of crop rotation was insignificant. All treatment plots under NT had less runoff at the start of the simulation with visible runoff believed to result soon after soil saturation.

Similar responses were observed for the main effects, where visible improvements enhanced with conservation agricultural practices (Figure 4.3 and 4.4). Conventional tillage had more soil loss (0.28 t/ha) and surface runoff (3.17 ml/s) than no-tillage (0.20 t/ha) and (3.10 ml/s), crop diversification reduced soil loss to (0.19 t/ha) and runoff to

(3.07 ml/s) compared to monocropping (0.31 t/ha) and (3.24 ml/s) (Appendix 3). Likewise, crop residue retention practices reduced soil loss (0.21 t/ha), and runoff (3.06 ml/s) compared to crop residue removal practices (0.27 t/ha) and (3.21 ml/s), respectively (Appendix 3). Conservation agriculture reduced water induced soil erosion in the medium to long term implementation. These results signify the returns of CA in soil conservation and sustainable farming for the present and future agricultural produce.

Table 4. 2: Analysis of variance (ANOVA) showing soil loss, runoff, and runoff coefficient in the sub-humid region of the Eastern Cape, South Africa

Treatment	Soil loss and runoff		
	Soil loss	Runoff	Runoff coefficient
T	***	ns	***
C	***	ns	**
R	***	**	***
T x C	ns	ns	ns
T x R	**	ns	*
C x R	*	ns	ns
T x C x R	ns	ns	ns
CV	10.40	4.58	2.73

ns = treatment not significant at $P \leq 0.05$ probability level; *, **, *** = treatment significant at $P \leq 0.05$, 0.01 and 0.001 probability level, respectively. T = tillage; C = crop rotations; R = residue management; T x C = interaction of tillage with crop rotations; T x R = interaction of tillage with residues; T x C x R = the interactions of tillage, crop rotations and residue management.

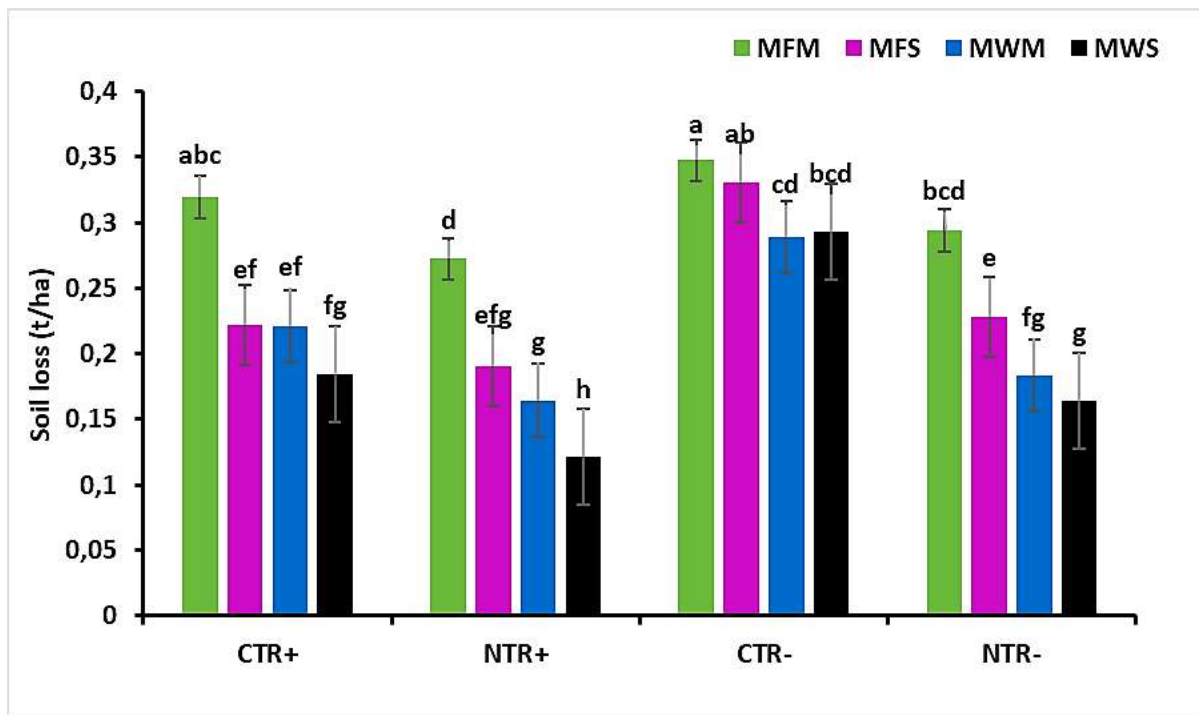


Figure 4. 3 : Interactive effect of tillage, crop rotation and crop residue management practices on soil loss at Phandulwazi conservation agricultural project

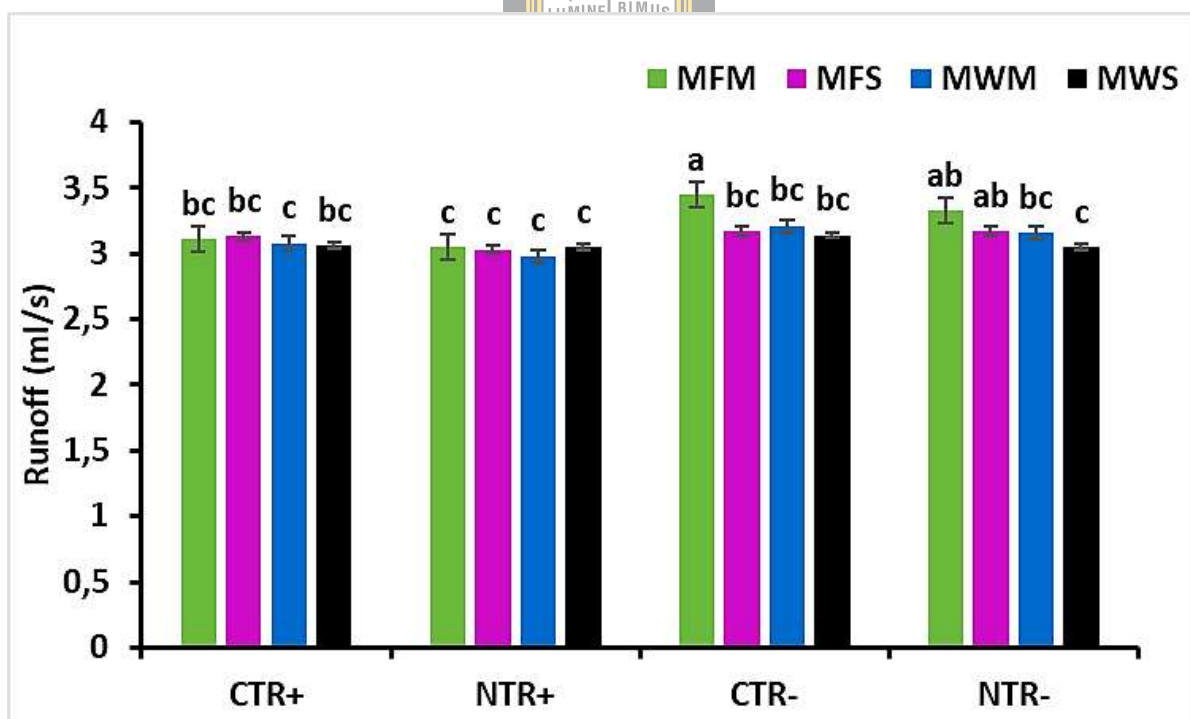


Figure 4. 4: Interactive effect of tillage, crop rotation and crop residue management on runoff at Phandulwazi conservation agricultural project

4.4.2 Principal component analysis and multiple linear regression

The principal component analysis (PCA) showed that the variation in soil bulk density, mean weight diameter (MWD), mass wetness, saturated hydraulic conductivity, porosity, runoff and soil loss measured in a CA trial accounted for 68.1 of variation from PC1 (53.5%) and PC2 (14.6 %) (Figure 4.5). PC1 was positively correlated with mass wetness, porosity, MWDdry, and MWDwet and negatively correlated with BD, soil loss, and runoff. On the other hand, PC2 was positively correlated with mass wetness and saturated hydraulic conductivity and negatively correlated porosity, MWDdry, and soil loss (Figure 4.5). In addition, the PCA figure more so presented the interlinked relationship between BD, mass wetness, Ks, porosity as well as soil aggregate stability (MWDdry and MWDwet) by showing their correlations, expressing their influence amongst another. The figure visualizes the increase on some parameters on one side with an increase of the others on a different side of the Cartesian plane reflecting their direct and inversely proportional relationship (Figure 4.5). BD, runoff and soil loss had strong negative loading matrixes while other physical properties (i.e. θ_m , ϕ and MWD) showed significant positive loadings except for Ks (Appendix 5).

The stepwise regression analyses showed that bulk density (BD) and mass wetness (θ_m) had significant with both positive and negative correlations with soil loss, respectively. Likewise, BD and porosity had similar correlations with runoff.

The soil loss equation is as follows: $Soil\ loss = 0.429135 * (BD) - 0.00469 * (\theta_m) - 0.25756$. This equation was used to compute soil loss from the collected data and the relationship was good with the coefficient of determination (R^2) of 0.766 and a root mean square error (RSME) of 0.059 (Figure 4.6). The runoff equation was developed and obtained as follows: $Runoff = 1.837065 * (BD) + 0.002862 * (\phi) + 0.308262$. This equation had a coefficient of determination (R^2) of 0.486 with a root mean square error (RMSE) of 0.207 (Figure 4.7).

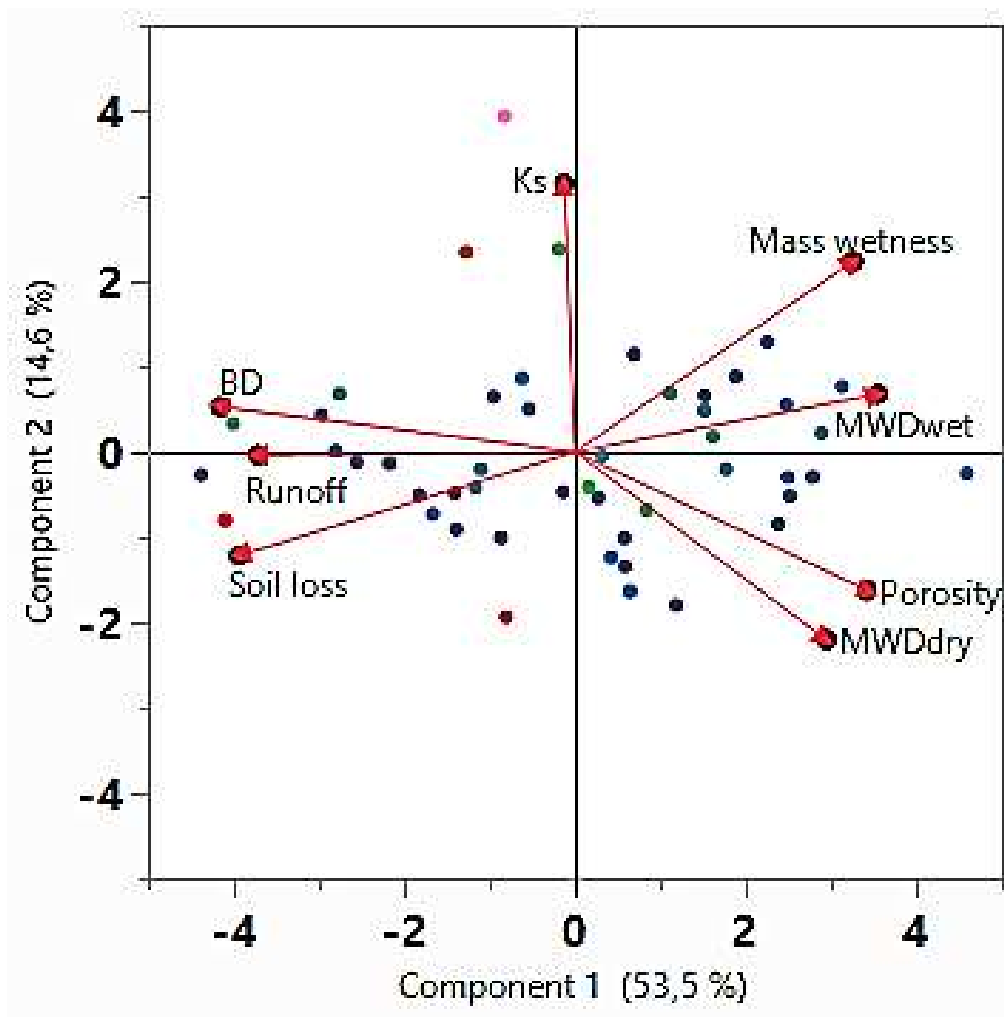


Figure 4. 5: Principal component analysis (PCA) showing the relationship between soil aggregate stability indices [mean weight diameter (MWDdry and MWDwet)], soil physical properties [Porosity, Mass wetness, Ks, BD] as well as soil loss and runoff, at 0–10 cm soil depths

Abbreviations: BD, soil bulk density; Ks, saturated hydraulic conductivity.

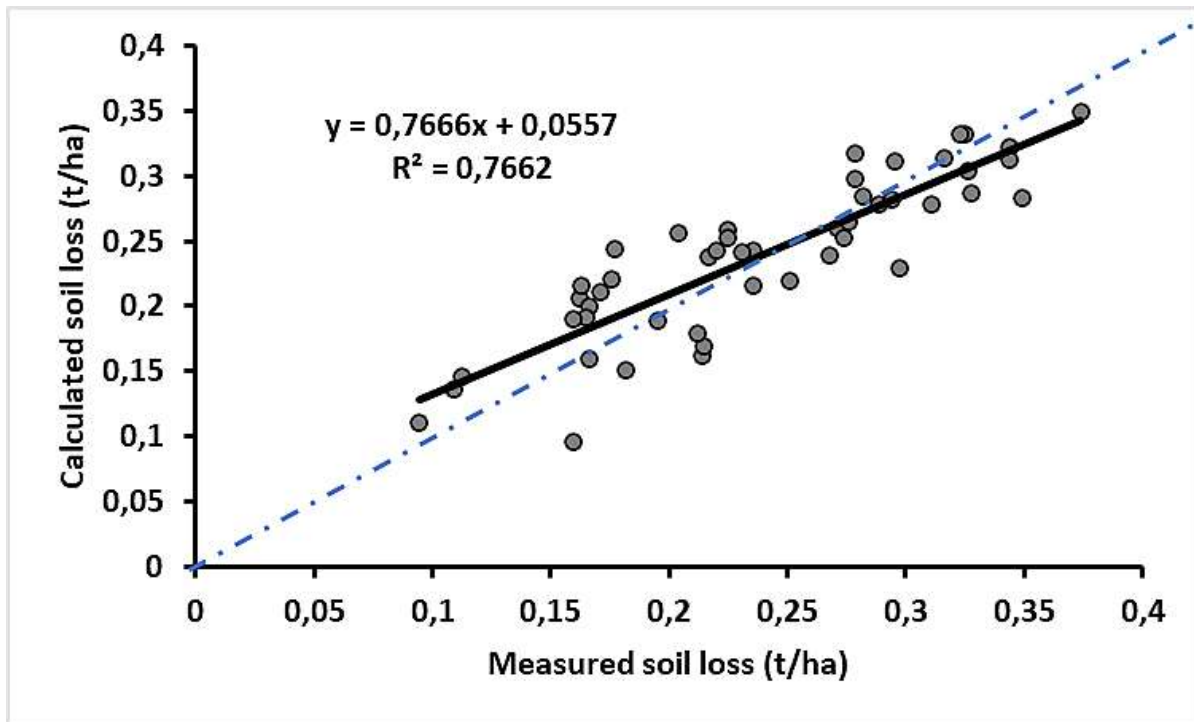


Figure 4. 6: Comparison between measured and predicted soil loss (t/ha) at Phandulwazi conservation agricultural trial

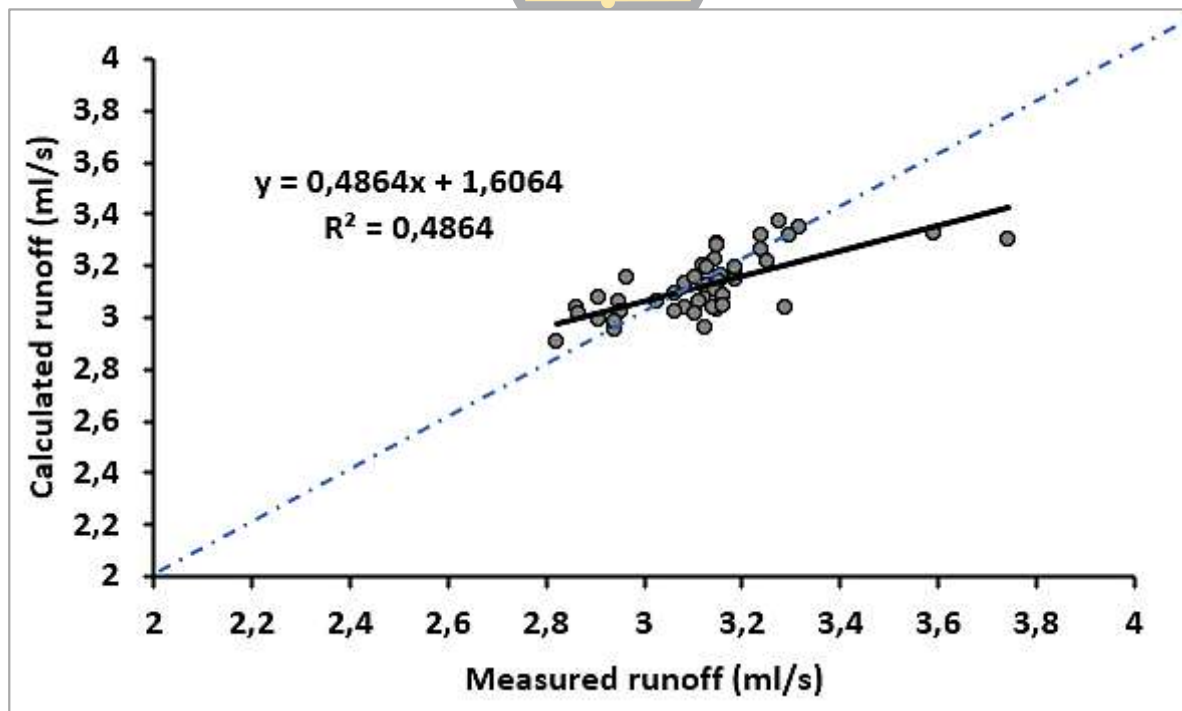
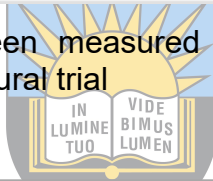


Figure 4. 7: Comparison between measured and predicted runoff (ml/s) at Phandulwazi conservation agricultural trial

4.5 Discussion

Soil loss by water erosion from rain-splash occurs through weak flows as sheet erosion, and heavy flows as rill or gully erosion. Sheet erosion, being the displacement of the upper layer of soil, leading to the exposure of the underlying subsoil (Apollo *et al.*, 2018), is the dominant cause of soil loss throughout SA (Le Roux *et al.*, 2008). However, CA protects the soil against erosive forces, improves roots anchorage onto the soil and enhances soil structural development and stability that CT impairs.

4.5.1 Effect of tillage, crop rotation and crop residue management on soil loss

The low soil loss observed for all plots under no-tillage system corresponds with observations by Caires *et al.*, (2005) where no-tillage system decreased erodibility that conventional tillage causes in soils, particularly, sandy loam soils. Although tillage loosens the soils which can improve water penetration, it contributes to unstable soils prone to erosion by water. No-tillage on the contrary enhances soil's stability as observed from the improved BD, AGS, and porosity (Chapter 3) hence becoming resistant to disintegration by water. Thierfelder and Wall (2012) also established greater cumulative soil erosion from CT treated fields compared to CA fields.

The highest soil loss from plots under mono-cropping (MFM) could be due to the exhaustion of certain nutrients (such as nitrogen) from the soil overtime making it infertile and bare (Magdoff *et al.*, 2021), hence susceptible to degradation forces (Figure 4.3). Maize crop on MFM takes up nitrogen and is not returned as the plots are under a monoculture treatment. On the other hand, MWS treatment plots have nitrogen fixing soybean legume crop in rotation that return nitrogen back to the soil. High sediment detachment observed at the beginning of the simulation (rainfall shower), symbolized sheet erosion. Transportation of the surface solid sediments by water runoff revealed the underground layer, this impairs the quality of soil and hence contributes to yield decline. However, the reduction in soil loss from monocultural production (MFM) to crop diversification (MWS) is because rotation with forage crops contributes to aggregates development which are essential for erosion control. Diversified crop cultivation returns high OM which with its binding products (i.e. sticky substances from soil invertebrates, fungal strands from microbial activities, and humus colloids reactions with soluble bases) from decomposition improves stable aggregates (Blanco-Canqui and Lal, 2004; Sarker *et al.*, 2022), hence reducing sediment deployment. Furthermore, maize–wheat–soybean crop rotations provide various root

types; from fibrous, adventitious and tap rooting systems, that trap and bind the soil particles as also explained in the study by De baets *et al.*, (2007), that crops cover and attach soil particles through root anchorage. The continued cultivation on MWM and MWS plots likewise reduced erosion through facilitated soil cover and anchorage by seasonally planted crops, in contrast to the fallow MFM and MFS plots that are susceptible to erosion by water due to exposure that accelerates the degradation processes.

Shaver *et al.*, (2002) explained the effects of crop residues especially under NT to contribute to an increase in total and effective porosities with soil aggregates and better soil structure, this can be a result of reduced soil loss & runoff under crop residue retained treatment plots. Crop residues generally contribute to lower surface runoff and soil loss by serving as a protective cover to the soil, minimizing evaporation (FAO, 2019). Residues retained on agricultural fields further reduces the raindrop energy (force and velocity) by preventing destruction of soil aggregates that make the soil erodible (Mhazo *et al.*, 2016) and increase the soil's permeability (Wainwright *et al.*, 2002). Erodibility is thus reduced on covered land surfaces. Moreover, the uppermost unstable soil particles are trapped and protected by crop residues, sediment transport is controlled, yielding less erosion by water. Similarly, a study under rainfed conditions in Ethiopia (Oicha *et al.*, 2012), comparing CA and CT after 4 – years declared decrease in soil loss and runoff from enhanced permeability and hydraulic contents under CA. The first hypothesis was accepted as reduced soil loss has been observed with CA implementation in the study.

4.5.2 Effect of tillage, crop rotation and crop residue management on runoff

Conservation agriculture normally improves water infiltration and enhances the soil's hydraulic potential hence reducing runoff (Thierfelder *et al.*, 2015). Reduction in average runoff under NT treatment plots contrasted to CT plots in this study coincides with observations from studies by (Mupangwa and Jewitt, 2011) on sandy clay loam soil, and clay loam soil (Mupangwa *et al.*, 2013), respectively, where authors reported high surface runoff on fields under CT than NT. These findings are ascribed to the fact that CA with NT treatment plots are better aggregated and well structured, enabling sufficient flow of water within soil particles as presented in Chapter 3. NT plots consequently showed enhanced soil mass wetness with improved porosity (Chapter

3). Whereas water accumulation at the top (surface) in response to compaction is the reason for high runoff in CT treated fields (Figure 4.4).

Plots under a series of crop diversification have high plant canopy, the soil is therefore protected from intense rainfall that distorts and erode soil particles. Highest runoff from a monoculture (MFM) in contrast to the low runoff from rotation of three crops (MWS) aligns with research on soil hydrology by Thierfelder and Wall (2009), who validated that CA systems on different soils and locations had improved infiltration and better water retention than CT. Rotational cropping enhances soil health and influences various soil lifeforms (flora and fauna) that aid in soil structural development (Yang *et al.*, 2020).

Much deposition of soil solid sediments from plots with residues removed and left bare during fallow, was due to surface compaction that restrict water percolation into the soil matrix, hence increasing runoff (Figure 4.4), an increased surface runoff generally related to enhanced soil sediment deposition. The low runoff obtained from plots with residues retained than that from plots with residues removed is in line with the findings by Araya *et al.*, (2012) and Molla and Desta, (2022) where crop residues were found to absorb raindrop impact and enabled improved infiltration of water than flowing over the soil. Crop residues have an essential interlinked relationship with soil indices, they serve as physical barriers and reduce sediment flow at the soil surface (De Baets *et al.*, 2007; Zuazo and Pleguezuelo, 2008) and hence allow infiltration and percolation, as supported by less runoff coefficient on covered plots. Runoff reduced with conservation agricultural practices; therefore, the second hypothesis was accepted.

4.5.3 Principal component analysis and multiple linear regression

This study correlated soil physical indices with soil loss and runoff. The PCA illustration between soil physical indices as well as soil loss and runoff have showed that soil structure (by virtue of aggregation, porosity and compactness) plays a crucial role in soil erodibility as presented by high loading values. The negative correlation between soil loss and AGS was because soils that are well aggregated/ structured are stable and resistant to disintegration, water infiltrates on porous soils and encourages easy flow of water within soil particles and hence deep percolation. In contrast to the compacted soils that lead to surface runoff accompanied by soil solids within the sediment deposition. Notably, K_s and θ_m strongly correlated, as K_s increases with increasing soil moisture content until full saturation (Thomas *et al.*, 2016). Reduced

porosity on the contrary, results from poor structure and aggregation, which contributes to low soil stability and high soil loss, as expressed by the negative correlation of soil loss and porosity as well as the positive correlation of structural indices (MWD_{dry} and MWD_{wet}) with porosity (Figure 4.5).

BD is highly correlated with soil loss, it generally has a strong effect on erosive forces and the amount of water infiltrating, percolating and retaining within the soil particles. This necessitates careful consideration of BD and θ_m as parameters of high impact pertaining to soil loss by water.

High correlation coefficient (R^2) from multiple linear regression analysis enabled estimations of soil loss from BD and mass wetness (θ_m) (Figure 4.6), which are the main determinants of soil erosion; with BD giving insight of soil compaction (soil structure and aggregation), mass wetness on the other hand presenting the soil's capability in water retention, thereby elucidating the infiltration, percolation and permeability or hydraulic conductivity potential that ultimately influence the rates of erosion and degradation. Research on soil erosion prediction uses the revised universal soil loss equation (RUSLE) model and quantifies the "K factor", a measure of a soil's susceptibility to erosion; used to estimate how much soil is lost each year. The K-factor is regulated by the soil's structural/ textural aggregate stability (Qian *et al.*, 2022), organic matter, and others include K_s (Ghavami *et al.*, 2024). These parameters are proxies of BD and θ_m , hence the model developed from this study. The strong positive association between the predicted and the actual measured soil loss (Figure 4.6), as well as the low root mean square error (RMSE), outlines the reliability of using BD and θ_m as input variables in the developed model and overall model's accuracy. However, the model still needs to be validated further for adequate and explicit utilization.

The poorer correlations of runoff with selected soil physical properties than soil loss is because runoff is mainly influenced by the rainfall intensity, topography and soil type (Mohamadi and Kaviani, 2015), all of which were constant in this study. Porosity influences water percolation, this explains its high negative correlation with runoff, bulk density on the other hand explains the extent of soil's structural quality which influences surface infiltration and the rate of runoff. The model presented low coefficient of determination (R^2) which reduces its accuracy in forecasting runoff using

BD and porosity, validation would however give more insight to its reliability and suitable utilization.

4.6 Conclusion

The aim of this chapter was to explore the response of CA system on soil erosion using simulated rainfall. Highest soil deposited sediments were from MFM treatment plots compared to other treatments and highest surface runoff was on plots with least number of rotations coupled with fallow periods (MFM and MFS) compared to those under rotation with multiple crops (MWM and MWS). The results showed that reduced tillage improved soil structural development and stability while diverse cropping improved roots anchorage, and crop residues reduced the impact of raindrops thus protecting the soil against erosive forces that detaches soil particles. Moreover, this study correlated soil properties with soil loss and runoff thereby elucidating significant role played by soil structural indices on soil erodibility. BD and θ_m predicted soil loss with high correlation coefficient (R^2) and low root mean square error (RMSE); thus, suggesting a strong reliability. BD and ϕ predicted runoff with relatively low R^2 . Further evaluation and validation of the developed models however remains crucial.

Through proper management of the agricultural fields and adoption of versatile conservative agronomic practices, soil erosion is reduced, and lower soil degradation rates are achieved. Hence, a strategic design of sustainable land management practices needs to be employed without negatively affecting productivity. Further investigation of soil erosion and measuring nutrient loss within sediment deposition is ideal for future studies.

CHAPTER FIVE

5.1 General discussion, conclusions and future research

The study aimed to evaluate the interactive effect of tillage, crop rotations and residue management practices on selected soil physical properties and soil erosion by water on a haplic plinthosol of the Eastern Cape, South Africa. The literature reviewed in Chapter 2 outlined soil degradation as the main threat contributing to lowered soil quality and ultimately loss of crop productivity, particularly resulting from a conventional farming system. Soil tillage has been found to predominantly contribute to soil degradation (Watson *et al.*, 2000; Caires *et al.*, 2005; Le Roux, 2011; Lal, 2015; FAO, 2021; Nyambo *et al.*, 2022). The literature also highlighted conservation agriculture as the control measure to address degradation and improve soil quality through sustainable agronomic practices (Mtyobile *et al.*, 2020; Muzangwa *et al.*, 2021; Nyambo *et al.*, 2022; Gura *et al.*, 2022; Myeni *et al.*, 2023).



The introduction of CA in the Eastern Cape province has not yielded desired results (Mtyobile *et al.*, 2020), the acceptance of CA under the smallholder has always been low, though research has been done to ascertain the CA practice in the short term (Mtyobile *et al.*, 2020; Nyambo *et al.*, 2022; Gura *et al.*, 2022). Limited research remains on the medium to long term CA effects, apart from handful assumptions and estimations quantified from the observed responses or through data modelling from other nations. Therefore, the research was focused on the two explicit objectives: (i) effects of conservation agriculture after a decade on selected soil properties and (ii) effects of CA after a decade on soil loss and runoff.

5.1.1 Bulk density, particle density and porosity

The topsoil correlation analysis between BD and ϕ (Table 3.6), presented a negative relationship amongst these soil physical parameters as decrease in BD (less compaction)

enhances pore distribution hence improved porosity. High BD observed under mono-cropped (MFM) treatment plots, especially with removed residues is reflected in Chapter 4 through limited permeability (infiltration) and high surface water runoff, hence more susceptibility to erosion. However, the reduced BD on MFS (rotational cropping) in relation to MFM treatment is possibly due to variations in crop root types as well as residual breakdown of soybean and maize crops as explained by Nebo *et al.*, (2020). Soybeans are reported to have the capacity to develop macropores thus decrease BD when it has decomposed (Kavdir *et al.*, 2005). Correspondingly, lower BD under MWM and MWS can possibly result from improved aggregate stability influenced by the continued accumulation of maize and wheat residues on plots under residue retention treatment. The research observations presented that BD and ϕ were significantly affected in the medium to long term CA adoption. The topsoil BD under NT reduced by 5.29% from CT (1.51 g.cm⁻³) and NT (1.43 g.cm⁻³). These findings were similar to reports by (Grossman and Reisch, 2002; Veenstra *et al.*, 2006; Nyamadzawo *et al.*, 2007; Abid and Lal, 2008; Nyambo *et al.*, 2018) where NT showed a reduced BD compared to CT. Transition from CT to NT lowered soil compaction in the extended term; therefore, no-tillage system can possibly improve soil conditions in the Eastern Cape Province (Nebo *et al.*, 2020), and potentially reduce degradation.

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5.1.2 Soil gravimetric water content, volumetric water content and saturated hydraulic conductivity

Soil moisture improved with CA implementation as more water could be retained within soil pores on well-structured CA soils. A positive correlation was observed amongst θ_m and soil aggregate stability indices (MWD_{dry} and MWD_{wet}) across the topsoil (Table 3.6), this highlights that soil water availability is influenced by aggregation. Correspondingly, surface runoff was reduced on CA plots, as also shown by reduced runoff coefficient, and hence limited soil loss through sediment deposition (Figure 4.4).

Contradictory trends on K_s relating to its response to CA systems have been outlined in literature (Hu, *et al.*, 2009). Kodešová *et al.*, (2009) and Kargas *et al.*, (2012), found high

average Ks on NT to result from improved SOM and plant root influence which led to an improved structure and pore distribution of the soil. Also, Moreno *et al.*, (1997) suggested that earthworm activities carving flow paths, especially under NT, influence water movement and storage within the soil by impacting porosity and soil water content. Though Ks did not respond significantly in this study, soil structural improvements (i.e. presented by enhanced MWD and porosity, as well as reduced BD) on CA plots aid in pronounced infiltration which control surface runoff and soil loss; this was verified through high θ_m and Ks on CA treated plots with low runoff and soil loss.

5.1.3 Soil structural aggregate indices (MWD_{dry}, MWD_{wet} and SI)

Improved OM on CA practiced plots led to developed structural aggregation and biotic diversity (soil flora and fauna) (Jefferson *et al.*, 2016), this ultimately impact soil moisture as infiltration is improved with eased water percolation through channels by macro-organisms. The benefits from CA as outlined on the previous chapters influenced both soil loss and runoff through reduced erodibility by soil structural improvement and enhanced stability of soil aggregates.

5.1.4 Medium term conservation agricultural effects in contrast to short-term

A short-term study following similar methodology was conducted by Gura *et al.*, (2022) on the same trial with CA effects on soil physical properties contradicting the current mid-term results. Briefly, only tillage practice was found to be dominantly effective on soil physical indices. BD was higher on NT than CT due to soil loosening with increased porosity during tillage. Contradictory to the short-term findings, this study had low BD on NT than CT as BD on NT initially increases up to reaching equilibrium; where the soil structure fully rebuilds, then proceeds reduction thereafter (Kinsella, 1995). These reflects soil structural build-up and enhanced soil quality on NT overtime.

The short-term study further found fallow practice (MFM and MFS) to result in AGS improvement than frequent cultivation, this was due to less soil disturbance under fallow practice as minimal soil disturbance result in better soil structure and aggregation.

Nevertheless, AGS on conventionally treated plots was poor compared to conservation (CA) plots in the mid-term due to improvements facilitated by NT under CA processes overtime, crop diversification with continuous cultivation (MWM and MWS) added more biomass hence encouraged high SOM accumulation that eventually led to enhanced soil structural aggregation (Saha *et al.*, 2010). The diverse crop residues with their binding products (formed during decomposition) further act as an adhesive on the soil particles (Blanco-Canqui and Lal, 2004; Sarker *et al.*, 2022), thereby improving AGS. These observations showed that crop residues retention improved the soil status through numerous interconnecting soil processes on extended periods (Cherubin *et al.*, 2021).

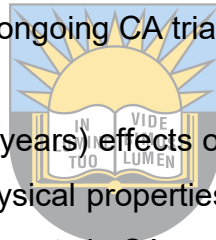
5.2 General conclusions

In general, the effects of CA system on soil properties are clearly noticeable in the long-term, especially in the topsoil. With the major objectives of the study highlighted in the previous chapters, soil physical properties and degradation by water erosion is controlled through full CA practice, thus it can be concluded from the findings that:

- Soil tillage practices significantly affect various soil physical properties, especially BD, ϕ and AGS. BD reduced on NT than CT. ϕ was greater on NT than CT plots. Likewise, AGS showed improvements on NT than CT.
- Crop rotations or diversification with soybean legume inclusion notably reduce surface runoff. Moreover, soybean decomposition improves soil structural indices (MWD and SI).
- Crop residues or cover crops protects the soil surface and promotes soil moisture, enhanced soil structural aggregation and reduced surface runoff and soil loss.
- Time is a critical factor in soil rehabilitation through conservation agriculture as some improvements becomes more apparent in the long-term. This study serves as a baseline for data acquisition to evaluate the individual effect of time.

5.3 Recommendations for future research

- Research on bulk density (BD) response from crop cultivation to time of harvest within one growing cycle/season, as numerous studies including this one; concluded that tillage temporarily reduces BD, followed by a rapid soil compaction, leading to increased BD within one crop growing cycle/season. Moreover, CT might result in the development of a plough sole and that might need to be investigated.
- Time of sampling pertaining crop effect on CA fields is critical, as this study acknowledges that the timing of soil sampling can influence the results (i.e. sampling after harvest or after planting is different). Research on the effects of sampling schedule within an ongoing CA trial would therefore expand literature.
- Research on long-term (>30 years) effects of conservation agriculture on various soil quality indicators and physical properties is essential, as time is a significant factor in soil quality enhancement via CA practice.
- Evaluation of time as a factor in soil re-integration through CA practice.
- Examination of soil erosion with nutrient loss measurements is ideal for future research. Quantification of the overall nutrient deposition from the agricultural field to the bellow lying areas and nutrient stratification (especially in the NT system) is crucial for soil quality and productivity assessment.
- Strengthening the adoption of CA by communal farmers through knowledge sharing and results presentation from such studies showing positive returns from the practice could improve CA implementation withing the small-scale farming



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sector. Research findings on soil degradation and hydric erosion should be shared amongst farmers to better their implementation of conservative agronomic systems.



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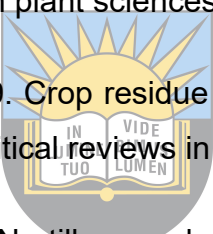
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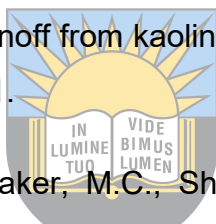
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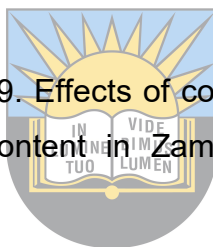
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Index

SA – South Africa

EC – Eastern Cape

CA – Conservation agriculture

ANOVA – Analysis of variance

ns – Not significant

T – tillage

C – Crop rotation

R – Residue management

NT – No-tillage

CT – Conventional tillage

MFM – Maize fallow maize

MFS – Maize fallow soybean

MWM – Maize wheat Maize

MWS – Maize wheat soybean

R+ – Residues retained.

R- – residues removed.

AGB – Above ground biomass

Bd – Bulk density

P_s – Particle density

K_s – Saturated hydraulic conductivity

AGS – Aggregate stability of soil

MWD – Mean weight diameter

MWDwet – Wet mean weight diameter

MWDdry - Dry mean weight diameter

SI – stability index

PCA – Principal component analysis

Θ_m – Gravimetric water content or mass wetness

ϕ – Porosity

Θ_v – Volumetric water content



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Appendices

Appendix 1: Ethical clearance for conducting the MSc study involving field and laboratory experiments



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INTER-FACULTY HUMAN RESEARCH ETHICS COMMITTEE (IFHREC) ETHICS CLEARANCE

Ethics Clearance ref. number:	MAN011SNON01
Project title:	Medium-term effect of tillage, crop rotation and crop residues management practices on soil physical properties, soil water erosion and water productivity in the dry land of Eastern Cape, South Africa.
Qualification registered for:	Master of Science in Agriculture: Soil Science
Student name:	Cossy Shayne Nonxuba
Student registration number:	201822111
Supervisor:	Prof A Manyevere
Department:	Soil Sciences
Co-supervisor:	Dr D Elephant Prod T Weldelessie

On behalf of the University of Fort Hare Inter-Faculty Human Research Ethics Committee (IFHREC) I hereby grant ethics approval for MAN011SNON01. This approval is valid for 12 months from the date of approval. Renewal of approval must be applied for BEFORE termination of this approval period. Renewal is subject to receipt of a satisfactory progress report. The approval covers the undertakings contained in the above-mentioned project and research instrument(s). The research may commence as from the 05/06/24, using the reference number indicated above.

Note that should any other instruments be required, or amendments become necessary, these require separate authorisation.

Please note that IFHREC must be informed immediately of

- Any material changes in the conditions or undertakings mentioned in the document;
- Any material breaches of ethical undertakings or events that impact upon the ethical conduct of the research.

The student must report to the IFHREC in the prescribed format, where applicable, annually, and at the end of the project, in respect of ethical compliance.

IFHREC retains the right to

- Withdraw or amend this approval if
 - Any unethical principal or practices are revealed or suspected;
 - Relevant information has been withheld or misrepresented;
 - Regulatory changes of whatsoever nature so require;
 - The conditions contained in the Certificate have not been adhered to.
- Request access to any information or data at any time during the course or after completion of the project.

Your compliance with Department of Health 2015 guidelines and any other applicable regulatory instruments and with IFHREC ethics requirements as contained in relevant policies and standard operating procedures, is implied.

IFHREC wishes you well in your research.

Yours Sincerely,



Dr Aceme Nyika

Chairperson: University of Fort Hare Inter-Faculty Human Research Ethics Committee (IFHREC)

07 June 2024

Appendix 2 : ANOVA results for the medium-term effect of tillage (T), crop rotation (C) and residue management (R) practices and their interactions on selected soil physical properties in the sub-humid region of Eastern Cape, South Africa

Soil physical properties									
Treatment	BD	Ps	θm	θv	φ	Ks	MWDdry	MWDwet	SI
0 – 10cm depth									
T	***	*	***	*	***	ns	***	***	***
C	***	*	***	***	ns	ns	ns	***	ns
R	***	***	***	***	ns	ns	ns	**	ns
T x C	ns	ns	*	ns	*	ns	ns	ns	ns
T x R	ns	ns	ns	ns	ns	ns	ns	ns	ns
C x R	ns	ns	***	ns	*	ns	ns	ns	ns
T x C x R	*	ns	*	ns	ns	ns	ns	ns	ns
10 – 20cm depth									
T	***	***	***	***	***	-	***	***	***
C	ns	ns	***	***	*	-	ns	**	ns
R	**	***	ns	ns	*	-	*	ns	*
T x C	***	ns	**	**	***	-	ns	ns	ns
T x R	ns	ns	ns	ns	ns	-	ns	ns	ns
C x R	ns	ns	ns	ns	ns	-	ns	*	***

T x C x R	ns	ns	*	*	ns	-	ns	ns	ns	ns
20 – 30cm depth										
T	ns	ns	ns	ns	**	-	**	***	*	
C	*	ns	***	***	*	-	***	***	**	
R	***	ns	**	**	***	-	ns	ns	*	
T x C	*	ns	*	ns	*	-	ns	*	ns	
T x R	ns	ns	*	ns	ns	-	ns	ns	ns	
C x R	ns	ns	***	**	ns	-	*	ns	*	
T x C x R	ns	ns	*	ns	ns	-	*	ns	ns	

T= tillage, C= crop rotation, R= Residue management system ns = treatment not significant at $P \leq 0.05$ probability level; *, **, *** = treatment significant at $P \leq 0.05$, 0.01 and 0.001 probability level respectively. BD = bulk density, Ps = particle density, θ_m = gravimetric water content, θ_v = volumetric water content, ϕ = porosity, Ks = saturated hydraulic conductivity, MWDdry = dry mean weight diameter, MWDwet = wet mean weight diameter, SI = stability index.

Appendix 3:Mean responses of main effects (tillage, crop rotation, crop residue management practices) on soil loss, runoff and runoff coefficient

Source of variation	Soil loss (MEAN)	Runoff (MEAN)	Runoff Coefficient (MEAN)
Tillage			
CT	0.28a	3.17a	51.39a
NT	0.20b	3.10a	48.68b
P Value	<0.0001	0.13	<0.0001
Crop rotation			
MFM	0.31a	3.24a	51.48a
MFS	0.24b	3.12ab	49.83b
MWM	0.21c	3.11b	49.80b
MWS	0.19d	3.07b	49.05b
P value	<0.0001	0.06	0.005
Crop residues			
R-	0.27a	3.21a	51.19a
R+	0.21b	3.06b	48.88b
P value	<0.0001	0.0012	<0.0001

CT= Conventional tillage, NT= No tillage, MFM= Maize-Fallow-Maize, MFS= Maize-Fallow-Soybean, MWM= Maize-Wheat-Maize, MWS= Maize-Wheat-Soybean, R-= Residues removed, R+= Residues retained.

Appendix 4: Mean table of interactions (tillage and crop rotation; tillage and crop residue management; crop rotation and crop residue management; tillage, crop rotation and crop residue management practices) on soil loss, runoff and runoff coefficient

Source of variation	Soil loss (MEAN)	Runoff (MEAN)	Runoff Coefficient (MEAN)
Interactions			
T x C			
CT x MFM	0.33a	3.28a	53.66a
NT x MFM	0.28b	3.19ab	49.29cd
CT x MFS	0.27b	3.15ab	50.87bc
NT x MFS	0.21d	3.10b	48.79d
CT x MWM	0.25bc	3.15ab	51.38b
NT x MWM	0.17e	3.07b	48.22d
CT x MWS	0.24cd	3.10b	49.65bcd
NT x MWS	0.014f	3.05b	48.43d
P value	0.156	0.98	0.09
T x R			
CT x R-	0.32a	3.24a	53.02a
CT x R+	0.24b	3.09bc	49.77b
NT x R-	0.22b	3.18ab	49.37b
NT x R+	0.18c	3.03c	48.00c
P value	0.002	0.94	0.04
C x R			
MFM x R-	0.32a	3.39a	53.47a
MFM x R+	0.29ab	3.08b	49.48bc
MFS x R-	0.27b	3.17b	50.72b
MFS x R+	0.21de	3.08b	48.93bc
MWM x R-	0.23c	3.19b	50.67b
MWM x R+	0.19e	3.03b	48.93bc
MWS x R-	0.23cd	3.1b	49.90bc
MWS x R+	0.15f	3.05b	48.18c
P value	0.04	0.15	0.22

Appendix 4 continues...

Source of variation	Soil loss (MEAN)	Runoff (MEAN)	Runoff Coefficient (MEAN)
Interactions			
T x C x R			
CT x MFM x R-	0.35a	3.45a	56.80a
CT x MFM x R+	0.31abc	3.11bc	50.52bcd
NT x MFM x R-	0.29bcd	3.33ab	50.14bcde
NT x MFM x R+	0.27d	3.05c	48.44def
CT x MFS x R-	0.33ab	3.17bc	51.35bc
CT x MFS x R+	0.22ef	3.13bc	50.38bcde
NT x MFS x R-	0.23e	3.17bc	50.09bcdef
NT x MFS x R+	0.19efg	3.03c	47.49f
CT x MWM x R-	0.29cd	3.21abc	52.39b
CT x MWM x R+	0.22ef	3.08c	50.37bcde
NT x MWM x R-	0.18fg	3.16bc	48.94cdef
NT x MWM x R+	0.16g	2.98c	47.49f
CT x MWS x R-	0.29bcd	3.14bc	54.50bc
CT x MWS x R+	0.18fg	3.06c	47.80ef
NT x MWS x R-	0.16g	3.05c	48.30def
NT x MWS x R+	0.12h	3.05c	48.57def
P value	0.38	0.87	0.07

CT= Conventional tillage, NT= No tillage, MFM= Maize-Fallow-Maize, MFS= Maize-Fallow-Soybean, MWM= Maize-Wheat-Maize, MWS= Maize-Wheat-Soybean, R-= Residues removed, R+= Residues retained, T x C= tillage and crop rotation interaction, T x R= tillage and crop residues interaction, C x R=crop rotation and crop residue interaction, T x C x R= Tillage, Crop rotation and Crop residues interaction.

Appendix 5: Principal component analysis of significant factors

Principal components	PC 1	PC 2
Eigen value	4.028	1.166
Percentage of variance	53.526	14.585
Cumulative percentage of variance	53.526	68.111
Loading values		
Runoff	-0.809	-0.007
Soil loss	-0.858	0.264
Bul density	-0.905	0.116
Mass wetness	0.710	0.487
Porosity	0.744	-0.352
MWDdry	0.641	-0.478
MWDwet	0.772	0.147
Saturated hydraulic conductivity	-0.027	0.685

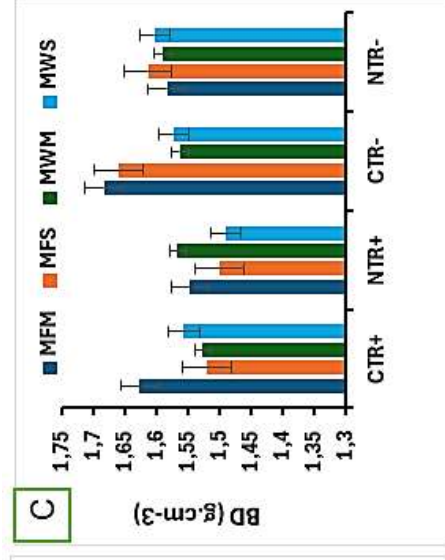
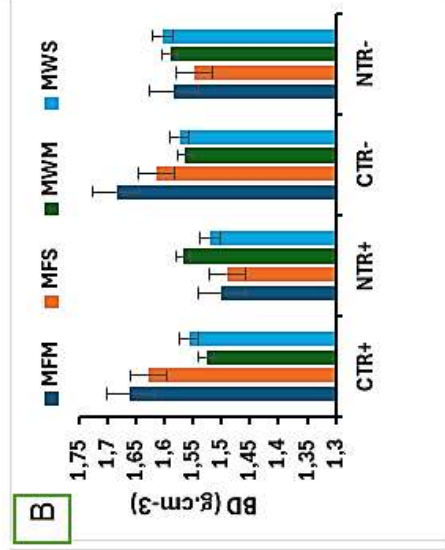
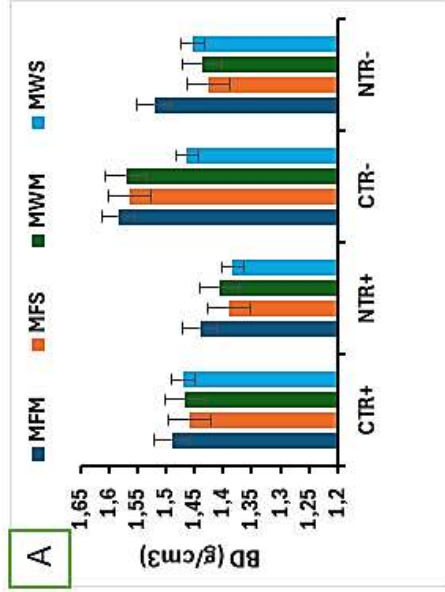
MWD, mean weight diameter.



Appendix 6: PCA table showing soil loss and runoff correlations with selected soil physical properties

	BD	θ_m	Porosity	MWDdry	MWDwet	Ks	Runoff	Soil loss
BD	1,00							
θ_m	-0,54	1,00						
Porosity	-0,82	0,21	1,00					
MWDdry	-0,53	0,21	0,53	1,00				
MWDwet	-0,59	0,56	0,46	0,49	1,00			
Ks	0,04	0,03	-0,01	-0,17	0,07	1,00		
Runoff	0.69	-0,52	-0,55	-0,43	-0,54	-0.02	1,00	
Soil loss	0,72	-0,81	-0,48	-0,41	-0,60	-0,01	0.63	1,00

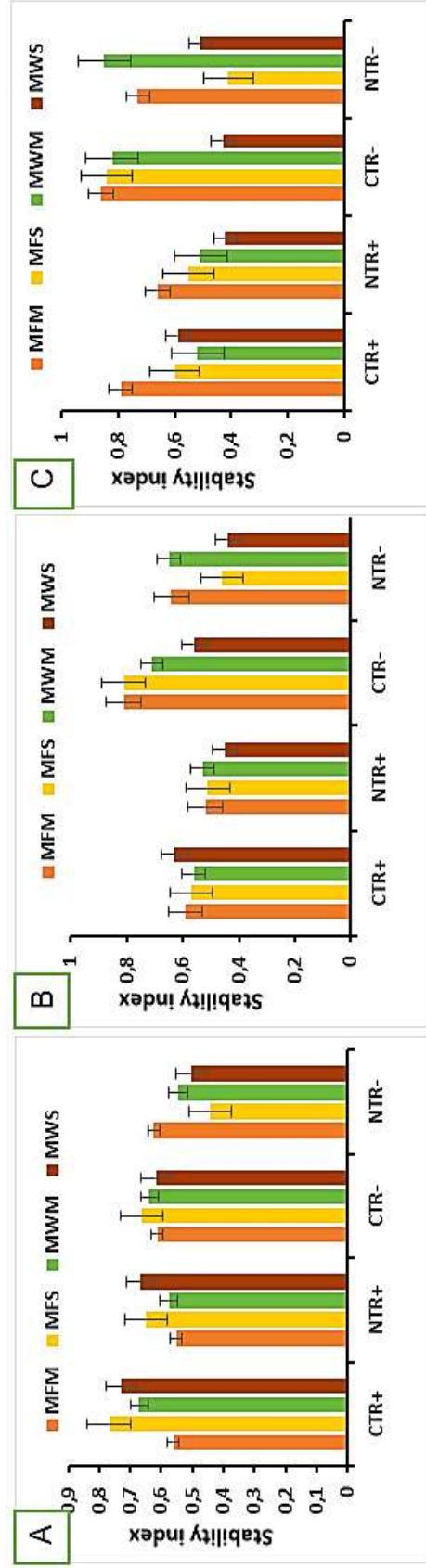
BD, bulk density; θ_m , mass wetness; MWDdry, mean weight diameter dry; MWDwet, mean weight diameter wet; Ks, saturated hydraulic conductivity.



Appendix 7: Interactive effect of tillage, crop rotation, crop residue management on bulk density (BD) at (a) 0 – 10 cm , (b) 10 – 20 cm and (c) 20 – 30 cm soil depth



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Appendix 8: Interactive effect of tillage, crop rotation, crop residue management on stability index (SI) at (a) 0 – 10 cm , (b) 10 – 20 cm and (c) 20 – 30 cm soil depth



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Appendix 9: Skeleton split split-plot ANOVA of blocks, tillage as main plot, crop rotation as sub plot and residue management as sub sub-plot factor

Source of variation	DF	SS	MS	F _{calc}	F _{tab}	
					5%	1%
Block	2					
Tillage (T)	1					
Error a	2					
Crop rotation (C)	3					
(C x T)	3					
Error b	12					
Residue management (R)	1					
R X T	1					
R x C	3					
R x T x C	3					
Error c	16					
Total	47					

F_{calc} calculated F-value

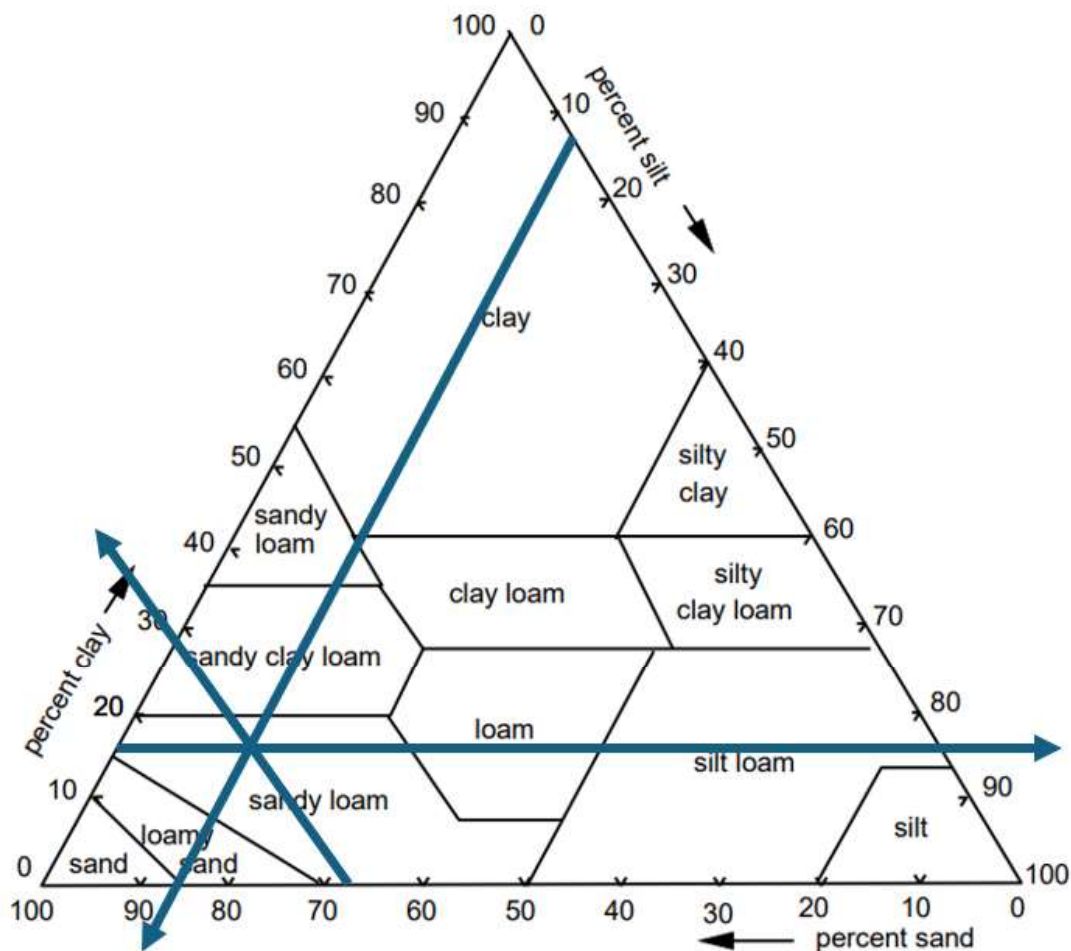
F_{tab} Tabular F-value at 5 and 1 % probability level



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Appendix 10: Soil information for the Phandulwazi conservation agricultural site

- The site had one soil type classified as the Avalon soil form according to the South African soils system of classification (Soil Classification Working Group, 2018); comprised of: an orthic A (≈ 35 cm thick), Yellow – brown apedal B (≈ 10 cm thick), and a soft plinthic subsoil (≈ 80 cm thick).
- Soil particle distribution ranged from: 65 – 72% Sand, 14.5 – 16% Clay and 13.5 – 18.5% Silt. The soil was identified as Sandy loam.



Soil textural triangle.