

**SORGHUM PRODUCTIVITY, ORGANIC CARBON AND SELECTED
SOIL QUALITY PARAMETERS UNDER SORGHUM-BASED
CLIMATE SMART AGRICULTURE ON SANDY SOILS UNDER SEMI-
ARID AND SUB-HUMID RAINFED CONDITIONS IN SOUTH AFRICA**

By

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**A thesis submitted in fulfilment of the academic requirements of Doctor of Philosophy
(PhD) in Soil Science**

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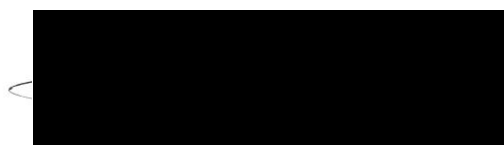
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ABSTRACT

The negative effects of intensive conventional tillage on infertile, sandy soils with low organic carbon (SOC), coupled with low water content and climate change, present significant challenges to smallholder agriculture, particularly under rainfed conditions. Conservation agriculture, which combines no-tillage (NT), residue retention and crop rotation, can improve soil quality. This study determined the effects of planting date (early and late), tillage (conventional tillage (CT) and NT, sorghum cultivar (Pan8816 and Macia), and crop rotation (with cowpea or continuous sorghum) on sorghum yield, soil water content, SOC and its fractions and microbial functional diversity on sandy soils within rainfed grain sorghum production systems, under semi-arid and sub-humid conditions. The study was conducted on sandy soils (<10% clay; <1.0% SOC) at Mphanama village (Limpopo Province) and at Clau-Clau village (Mpumalanga Province), South Africa. The experimental set up was a randomized complete block design (RCBD) with a strip-split-split-plot treatment structure, replicated three times. At Mphanama, early planting promoted greater plant height and thousand seed weight (TSW), while the interaction between early planting and NT increased sorghum yield in season three. Planting sorghum early significantly improved crop growth and yield in the second growing season, whereas late planting and planting under NT significantly increased TSW during the third growing season at Cla-Clau. No-tillage significantly improved soil water content at Mphanama and increased available phosphorus (P), potassium (K), and SOC in bulk soil and in all measured fractions at Clau-Clau, while CT significantly increased soil water content. Late planted sorghum significantly increased SOC, calcium (Ca), magnesium (Mg) during season two and increased fine particulate organic carbon (POC), acid phosphomonoesterase, microbial richness (R) and average well colour development (AWCD) index during season three at Mphanama. The NT treatment increased the microbial evenness (E) and decreased AWCD index in season three at Mphanama. Late planting and NT improved AWCD index in season three at Clau-Clau. The findings of this study suggest that the effects of planting time, tillage and crop rotation on soil properties in sandy soils are site specific possibly due to differences in climatic conditions and soil types. The findings will be useful in the selection of conservation agriculture systems, depending on the site properties and the objectives.

Keywords: Carbon fractions, crop rotation, soil microbial diversity, soil water content, planting date, tillage.

PREFACE

This thesis is composed of six chapters. Chapter one entails the general introduction, including the background, statement of the problem, research questions, aim, objectives and hypotheses of the study. Chapter two is the literature review, which outlines and discusses the status of knowledge on the benefits of conservation agriculture (CA) practice, in the context of climate variability and climate change, on cereal crop production and the response of soil quality particularly in sandy soils. It also demonstrates the challenges of adopting conservation agriculture (CA) in Sub-Saharan Africa and highlights the gaps in knowledge. Chapters three to five address the three outlined objectives which are written in a scientific article format. These three scientific article chapters are linked to each other and as a result, repetition could not be completely avoided. Chapter six discusses overall findings from chapters three to five, knitting the findings together. Appendices are provided at the end of the thesis.

DEDICATION

To my loving parents: Mabasa M.D and Masingi P.I, my siblings: Victor, Mushe, Nkhensani, Lazarus and Tintswalo. This thesis could not be successful without your support. Thank you.

LIST OF ABBREVIATIONS

ANOVA – analysis of variance

ARC – Agricultural Research Council

Ca – calcium

CA – conservation agriculture

CEC – cation exchange capacity

CT – conventional tillage

DOA – Department of Agriculture

EC – electrical conductivity

K – potassium

LAN – Limestone Ammonium Nitrate

MAOC – Mineral-associated organic carbon

MAP – Monoammonium Phosphate

Max – maximum

Min – minimum

Mg – magnesium

mg/kg – milligram per kg

NT – no tillage

OC – organic carbon

P – phosphorus

PD – planting date

PD1 – early planting date

PD2 – late planting date

PMC – potentially mineralizable carbon

POC – particulate organic carbon

POM – particulate organic matter

R1 – first rotation

R2 - second rotation

RCBD – randomized complete block design

S-C-S – sorghum-cowpea-sorghum

SOC – soil organic carbon

SOM – soil organic matter

SSA – Sub-Saharan Africa

S-S-S – sorghum-sorghum-sorghum

TN – total nitrogen

TSW – thousand seeds weight

t/ha – tonnes per hectare

V1 – Pan8816

V2 – Macia

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CHAPTER ONE

1.0. GENERAL INTRODUCTION

1.1. Introduction

Agricultural practices including continuous intensive ploughing, removal of crop residue from the soil surface, frequent burning of crop residues and intensive grazing accelerate soil degradation and threaten food security and the life of those who depend on agriculture in Sub-Saharan Africa (SSA) (Zingore et al, 2015; Araya et al., 2024). Soil degradation is particularly severe in South Africa because most soils have diverse inherent characteristics that render them structurally fragile and consequently highly susceptible to soil degradation (Le Roux et al., 2011; Collins et al., 2015; Manyevere et al 2016).

The high erodibility of the majority of SA soils, particularly those which are derived from shales and mudstones, is attributed to the exceptionally high content of silt, very fine and fine sand fractions in semi-arid regions, which is higher than other parts of the world, while in humid regions it is governed by the presence of oxides of aluminium (Al) and (Fe) (Manyevere et al., 2016). Furthermore, specific geological formations such as the Beaufort sediments (mudstone, sandstone, shale) and the Drakensberg group have excessive sodium concentrations, which causes dispersion of soil particles, (Van Tol et al., 2023). These inherent soil properties predispose these soils to degradation. This inherent fragility is worsened by the very low soil organic matter (SOM) concentration and poor soil management practices (Van Tol et al., 2023). Other widespread characteristics such as sandy texture further exacerbate these challenges by limiting water retention, reducing nutrient availability, and increasing vulnerability to erosion.

Sandy soils, widespread in many rainfed agricultural areas, are characterised by high sand content, which inherently leads to low water holding capacity, rapid nutrient leaching, and rapid SOM decomposition. These properties make sandy soils particularly vulnerable to climate change, which has intensified the occurrence of extreme weather events. In many areas, rising temperatures and declining precipitation are leading to hotter and drier conditions, reducing biomass production and increasing SOM oxidation (Mandal and Roy, 2024). The

combination of low biomass input and rapid loss of SOM further reduces soil aggregation and aggregate stability, increasing the risk of surface sealing, crusting, wind and water erosion. These negative effects could also be worsened by changes in rainfall characteristics particularly intensity, which can further increase susceptibility to sealing, crusting, erosion and SOM loss.

Extreme variations in temperature and precipitation influence soil drying and rewetting cycles, which are fundamental processes that affects SOM turnover, nutrient cycling, soil aggregation and carbon dioxide (CO₂) fluxes (Denef et al., 2001; Mikha et al., 2005; Najera et al., 2020). Previous studies demonstrated that CO₂ fluxes increase following rewetting of dry soils (Beare et al., 2009; Wu et al., 2010; Xiang et al., 2008) and decrease during drying (Joos et al., 2010), across different agricultural cropping systems. The increased decomposition of SOM during drying and rewetting cycles is due to soil microbial organisms responding quickly to changes in soil water content (Moyano et al., 2013). In addition, high temperature conditions further increase CO₂ emission due to C mineralisation and reduction of soil organic carbon (SOC), especially when soil water content is optimum (Wan et al., 2011).

Drying and wetting cycles of soil, coupled with rising soil temperature due to climate change can result in the depletion SOC within the soil (Li et al., 2020), although they may offer short-term benefits such as increased N and P availability (Gao et al., 2020). Denef et al. (2001) reported that soil macro- and micro-aggregates decreased within two weeks of drying and rewetting cycles compared to a control soil. The extent of this decline may depend on factors such as vegetation type, nature of the soil (Vargas et al. 2010), extent of physical protection of SOC (Von Lutzow et al. 2007), and agricultural practices (Denef et al., 2001), particularly under conventional tillage (CT), which remains the most practised method (Kumar et al., 2019).

Addressing the complex challenges of soil degradation and enhancing agricultural resilience under climate change requires the adoption of sustainable practices including climate smart agriculture (CSA). CSA is designed to achieve three key objectives i.e. to sustain agricultural production and income, adapt and build resilience to climate change, and mitigate the emission of greenhouse gasses (FAO, 2021). Amongst the key components of CSA, conservation agriculture (CA) has demonstrated promising improvements in overall soil quality, through mitigating many of the soil degradation issues caused by unsustainable practices and climate change.

As a key practice within the CSA framework, CA is based on three principles i.e. minimum soil disturbance, crop rotation and soil surface cover (mulch) using crop residues. These

practices have shown promising results in improving SOM and overall soil quality, with potential benefits including regulating soil water dynamics. This in turn influences critical soil processes and functions such as aggregation, mineralisation and sorption/desorption processes of N and P, among other nutrients. The enhancement of soil water conservation through CA, can help to reduce the negative climatic impacts on agriculture (Abdalla et al., 2016; Tarkalson et al., 2006), by increasing crop production compared to CT (Busari and Salako, 2013; Busari et al., 2015; Thierfelder and Wall. 2012). While most of the benefits of CA have been reported in wetter areas under maize-based cropping systems, climate change prompted recommendations to switch towards drought tolerant crops such as sorghum (*Sorghum bicolor*) in low rainfall areas (Hadebe et al., 2017a). Cropping systems significantly influence soil properties including soil aggregation, which affects the dynamics of nutrient mineralisation, particularly C, N and P (Lamparter et al., 2009). Nevertheless, little is known on how sorghum-based CA systems influences crop yields, SOC, N and P mineralisation, soil enzymes activities, soil microbial community and soil water dynamics in sandy soils.

Grain sorghum (*Sorghum bicolor* (L) Moench) is a C₄ cereal crop that is consumed as staple food by millions of people across various countries in Africa and Asia under low rainfall areas (Hariprasanna and Rakshit, 2016). Sorghum adapts very well under different soil conditions, including those prone to severe drought, where maize does not do well (Ratnavathi et al., 2011). This adaptability makes it one of the most suitable crops for inclusion in climate change adaptation strategies.

The benefits of CA on soil properties under grain sorghum have been previously reported (Mupangwa et al., 2012; Serme et al., 2015; da Silva et al., 2020). For instance, Mupangwa et al. (2012) reported higher sorghum grain yield under CA using a ripper system compared to CT systems. Additionally, the rotation of maize-cowpea-sorghum-maize resulted in more grain than the maize monocrop and maize-cowpea-maize under CA in a ripper tillage system. In sandy soils, the combination of no-tillage (NT) with soil mulch increased available N content (da Silva et al., 2020). Malobane et al. (2018) also reported that CA under sweet sorghum production improved biomass accumulation, which enhances SOM inputs, potentially improving SOC and soil aggregation. However, little is known about how sorghum-based CA systems influence soil water dynamics and nutrient cycling, which are critical in determining the resilience of crop production systems under adverse climate change conditions.

The predicted changes in climate are expected to affect rainfall distributions (Allen et al., 2011), which is likely to influence soil properties (Nciizah and Wakindiki, 2014). For instance, in semi-arid areas rainfall is projected to become less frequent while increasing the chances of drought events (Davis, 2010), thus potentially altering the dynamics of soil processes. The potential positive effects of sorghum-based CA systems on dynamics of soil water content could affect soil microbial activity and nutrient cycling, during the cropping season, which may likely result in increased grain and dry matter yields. The increased yield could enhance food security and household income, while increased dry matter positively contributes to improved livestock feed availability and greater SOM inputs. Therefore, this study aimed to evaluate the effects of planting date and CA on soil water content, soil nutrient cycling, and soil enzyme activities and microbial community functional diversity, during the cropping season under short-term grain sorghum production on sandy soils under semi-arid and sub-humid conditions with contrasting rainfall conditions.

1.2. Objectives

The main objective of the study was to evaluate the effects of conservation agriculture on soil water content, soil nutrient cycling, and soil enzyme activities and microbial community functional diversity on sandy soils from semi-arid and sub-humid regions of South Africa.

There were three specific objectives as follows:

- i. To determine the effects of planting date (early and late), tillage (NT and CT) practice, crop rotation (sorghum-cowpea-sorghum and sorghum-sorghum-sorghum), cultivar (Pan8816 and Macia) choice and their interactions on the grain sorghum growth, dry matter, yield and selected soil chemical properties.
- ii. To determine the effects of planting date, tillage practice, crop rotation and their interactions on soil water content, organic carbon (SOC) and its fractions (fine POC, coarse POC and mineral associated OC) as well as soil protein and SOC fractions in a grain sorghum production system.
- iii. To determine the effects of planting date, tillage practice and their interactions on soil enzyme activity (β -glucosidase and phosphomonoesterase) and soil microbial community functional diversity (amines, AWCD, carbohydrates, carboxylic acids and polymers).

1.3. Hypotheses

H₀: Early planting, no-tillage (NT) with crop residue retention, rotation with a legume will not improve:

- i. Sorghum dry matter, grain yield and the chemical properties of sandy soils in semi-arid and sub-humid climatic conditions.
- ii. Soil water content, SOC, soil protein and SOC fractions in sandy soils under grain sorghum-based CA in semi-arid and sub-humid climatic conditions.
- iii. The activities of β -glucosidase, acid phosphomonoesterase and the utilization of soil microbial community functional diversity in sandy soils in semi-arid and sub-humid climatic conditions.

H_a: Early planting, no-tillage (NT) with crop residue retention, rotation with legume will improve:

- i. Sorghum dry matter, grain yield and the chemical properties of sandy soils in semi-arid and sub-humid climatic conditions.
- ii. Soil water content, SOC, soil protein and SOC fractions in sandy soils under grain sorghum-based CA in semi-arid and sub-humid climatic conditions.
- iii. The activities of β -glucosidase, acid phosphomonoesterase and the utilization of soil microbial community functional diversity in sandy soils in semi-arid and sub-humid climatic conditions.

1.4. Research questions

- i. Do planting date, tillage practice, crop rotation, and cultivar influence sorghum growth, dry matter production, grain yield, and soil physicochemical properties in sandy soils under semi-arid and sub-humid conditions?
- ii. What are the effects of planting date, tillage practice, and crop rotation on soil water content, SOC, and soil protein and SOC fractions in a grain sorghum-based conservation agriculture system?
- iii. Do planting date and tillage practice affect soil enzyme activities (β -glucosidase and acid phosphomonoesterase) and soil microbial community functional diversity in sandy soils?

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Introduction

The major agricultural challenges in Sub-Saharan Africa (SSA) include rapid population growth and increased food demand, extreme soil degradation, climate change and increasingly uncertain rainfall distribution. Most of these factors collectively lead to declining crop yield (Battisti and Naylor, 2009; Sithole et al., 2016; Orimoloye, 2022). Population growth is expected to reach 9.8 billion by 2050, which will increase the demand for food (FAO, 2009; He et al., 2019). The challenge will be particularly more pronounced in arid and drought-prone regions (He et al., 2019). Recently, African countries including South Africa are facing a decline in agricultural production with some of the major production limitations linked to water scarcity due to extreme drought events (Tembile, 2021).

According to Lobell and Gourdji, (2012), the projected warming trends caused by high temperatures are likely to reduce crop yields by 1.5% per decade across the world. Luo (2011) concluded that, the productivity of maize, sorghum and wheat declines once the required temperature threshold is exceeded. Schlenker and Roberts (2008) predicted that crop yields will likely decrease by approximately 67 – 79% by the end of the 21st century because of the rapid rising temperatures in the United States, which contributes 41% of maize and 38% of soybeans in the world. A yield decline of more than 87% was observed when maize and potatoes were planted between 1.3 and 2.6 °C above the normal highest temperature occurrence in the tropical Andean region in Southern Peru (Tito et al., 2018). In SSA, the crop yields for maize, sorghum, millet and groundnut declined by 27 – 32% due to a temperature increase of 2 °C above the normal threshold by mid-century (Schlenker and Lobell, 2010). Furthermore, maize yield declines were 24% and 71% for beans due to warming exceeding 4 °C in SSA (Thornton et al., 2011). Cereal crops such as maize and sorghum are some of the vital staple crops cultivated for food and feed particularly in Africa and some parts of the world (Sithole et al., 2016).

Countries such as South Africa stand at a higher risk of crop failure because of water scarcity due to low annual rainfall (500 mm year⁻¹), drought and reliance on rainfed agriculture

(Seckler, 1998). Because of the current persistent drought in South Africa, the National Disaster Management Centre (NDMC) of South Africa has declared that more extreme drought events are likely to continue in South Africa (Tembile, 2021). Mostly, climate change impacts are more pronounced on sandy soils especially under poor management because of their inherently low water and nutrient holding capacity, higher water drainage and low SOC. Worldwide, sandy soils are widely distributed, covering various ecosystems (Huang and Hartemink, 2020). About 35% of sandy soils are reportedly barren, while 21% are under grasslands, 21% are covered by shrubland, 11% under savanna and 6% are forested (Earth Data, 2018; Huang and Hartemink, 2020). Globally, nearly 900 million ha of sandy soils are located in arid and semi-arid areas (Yost and Hartemink, 2019). In Africa, approximately 176 million ha of sandy soils are found in nine countries i.e., Angola, Botswana, Kenya, Mozambique, Namibia, Tanzania, South Africa, Swaziland and Zimbabwe, with over 15% area is covered with sandy soils in South Africa (Hartemink and Huting, 2005).

Sandy soils are characterized by a sand content of over >50% and clay content of less than 20% within 30 cm soil depth. This composition results in a high rate of water infiltration and renders sandy soils highly susceptible to drought (Hengl et al., 2017; Bockheim et al., 2020; de Holanda et al., 2023). When the sand content exceeds 70%, sandy soil exhibits significant deficiencies in both macro- and micro-nutrients (Li et al., 2022). The high content of sand and low clay, in sandy soils, promote water runoff and erosion, which leaches away soil nutrients, consequently, making sandy soil less productive. According to Huang and Hartemink (2020), sandy soil is more sensitive to anthropogenic processes and climatic forces than other soils, while De Holanda et al. (2023) emphasized that soil degradation is worse on these soils due to their fragility. Sandy soil has poor structure, lower SOC and poor water and nutrient holding capacity which negatively affect agricultural production and sustainability (De Holanda et al., 2023). Moreover, sandy soils have larger particles and lower specific surface area which reduces the ability to adsorb and retain nutrients or form strong bonds with organic matter leading to increased mineralization or rapid declines in SOC. These soils are also characterized by very low cation exchange capacity (CEC), base saturations and fertility which may be caused by the low SOC and clay content (De Holanda et al., 2023).

Consistent intensive ploughing of sandy soil exacerbates nutrient depletion by wind and water erosion as well as the rapid turnover of plant residues on the soil surfaces. The removal of these residues leaves the soil exposed to extreme temperatures, increasing soil water loss and erosion

while negatively affecting soil biological activity (De Holanda et al., 2023). Furthermore, the use of heavy machinery for ploughing intensifies soil compaction on sandy soils, which reduces void space, decreases soil porosity, and increases the bulk density (Shah et al., 2017). Soil compaction also negatively affects the decomposition of SOM by soil microbes, affecting nutrient recycling since soil microorganisms rely on the available pore space for movement and air and metabolic activities (Awasthi et al., 2022). Huang and Hartemink (2020) demonstrated that low compaction in sandy soils due to minimal use of heavy machinery for ploughing may actually improve agricultural production by enhancing soil water retention as well as nutrients use efficiency. Soil organic carbon is amongst vital soil quality indicators because it is linked to the physical, chemical and biological properties of the soil (Verhulst et al., 2010; Sithole et al., 2016).

Soil organic carbon improves soil structural stability by binding aggregates together and stimulating soil microbial community (de Holanda et al., 2023). Continuous ploughing depletes SOC since it involves the removal of soil cover and leaves less than 15% of crop residues on the soil surface, disrupting recycling of nutrients and reducing soil quality (Sithole et al., 2016). A meta-analysis research on SOC under cultivated soils of South Africa demonstrated that continuous intensive tillage on agricultural lands had resulted in loss of 25 – 54% of SOC in Southern Africa (Swanepoel et al., 2016). Authors illustrated that cultivation or any soil disturbance results in increasing the oxidation of crop residues which promote the release of CO₂ while reducing SOC. The same authors also demonstrated that intensive tillage weakened the positive relationship between SOC and clay content within the soil, consequently declining SOC. The content of SOC varies across climatic conditions. Yost and Hartemink (2019) reported that sandy soils in arid regions had lower SOC content (<5 g kg⁻¹) than those in temperate and cold regions (mean 19 g kg⁻¹). South African soils have relatively low levels of SOC which is mainly affected by the extreme warm temperatures which negatively affect the production of crop biomass (Du Preez et al., 2011). Generally, sandy soils have extremely low content of SOC particularly in those soils under CT. For example, the initial SOC was 0.45% within 0 – 15 cm (sandy loam) and 0.41% within 15 – 30 cm (sandy clay loam) in the study conducted by Swanepoel et al. (2018) at Buffelsvlei, South Africa. While Du Preez et al. (2011) reported that 58% of the South African soils have less than 0.5% of SOC, which could be influenced by extreme climatic events and the shift from humid to semi-arid conditions, consequently affected crop biomass production, a vital source of SOC. Higher temperatures accelerate the decomposition of SOC and release stored SOC into the atmosphere (Lenton and

Huntingford, 2003). According to Govaerts et al. (2009), the effective build-up of SOM often takes longer and it can even take decades. Effective CSA strategies are essential for improving the quality of soils, especially SOC levels, to enable the production of greater food, feed and fibre on marginal soils under a changing climate.

Conservation agriculture (CA) has been introduced under different regions, soil types, climate and different crops to improve agricultural sustainability (Malobane et al., 2020). The quality of SOC recycling profoundly relies on the types and the contents of the organic material additions (Vityakon, 2007). Therefore, the improvement and restoration of SOC in sandy soils require high inputs of organic materials. However, the adoption of CA in South Africa and some other parts of Africa has been very slow compared to other countries such as Australia and United States (Sithole et al., 2016). In South Africa (SA), the adoption of CA on agricultural lands is approximately 368 000 ha, which account to 7% of the cultivated land that was reported under NT practice in the year 2008/9 (Freidrich et al., 2012; Derpsch et al., 2014; Sithole et al., 2016). While other African countries including Mozambique, Zambia and Zimbabwe had recorded 152 000 ha, 200 000 ha, and 139 300 ha, respectively of CA adoption (Freidrich et al., 2012). Thus, low CA adoption in SA and other parts of the world may be due to lack of CA research training, lack of required CA implements and long-term turnaround benefits of CA for smallholder farmers. Understanding the appropriate agricultural practices and selection of smart-climate crops such as sorghum could improve soil quality and enhance agricultural sustainability under CA and on sandy soils. Therefore, this review aims to provide knowledge and a comprehensive understanding of the potential benefits of CA on soil quality and its impact on sorghum/maize-based production systems to increase food security and soil quality enhancement in sandy soils.

2.2. Conservation Agriculture

Conservation agriculture (CA) is an environmentally friendly agricultural practice which aims to achieve high agricultural productivity and sustainability (Edralin et al., 2016). It is based on minimal tillage, soil cover by plant residues, cover crops or mulches and crop rotation (Hobbs et al., 2008). Minimal soil disturbance is mainly achieved by NT or reduced tillage (RT) (Busari et al., 2015), which minimizes soil degradation, avoids the destruction of soil pores and mycorrhizal hyphae networks, and increases soil microbes after a few years of adoption

(Dittbrenner, 2019). It increases nutrient recycling, improves water infiltration and water holding capacity (Shaxson et al., 2008). While the maintenance of soil cover increases SOM, which promotes higher soil microbial activity resulting in improving nutrients recycling such as of N, improves soil structure, improved soil porosity, which promotes water infiltration (Hobbs et al., 2008). The CA system increases soil water availability by reducing evaporation (Ayman, 2023). Tuure et al. (2021), demonstrated that soil mulching using maize crop residues, conserved more soil water over time than plots without mulch. Another study showed that adoption of minimum tillage with mulch significantly increased soil water content in a maize cropping system under a sub-humid region in a loamy sand in Namibia (Kudumo et al., 2023). The absence of intensive ploughing coupled with crop rotations could be even more beneficial.

Crop rotation has positive effects in agricultural production because it protects crops against pest and disease issues by interrupting the life cycle of certain bacteria, fungi, insects and weed pests (Dittbrenner, 2019). Currently, CA has gained attention across the globe due to its enhancement on soil quality and crop yield improvement comparable to those mostly achieved by the commercial farming sectors (Hobbs et al., 2008; Swanepoel et al., 2018). A previous study on the benefits of crop rotation on wheat yield found that crop rotation increased wheat yields by 30% and 13% under NT and CT, respectively compared to monoculture on a sandy clay soil in the southwest of Finland (Jalli et al., 2021). However, CA adoption on agricultural lands in South Africa is extremely low with evidence of 368 000 ha, which account to 7% of the cultivated land that was reported under NT practice in the year 2008/9 (Derpsch et al., 2014; Sithole et al., 2016). The CA system influences soil quality and crop yield differently across regions because of differences in climate, vegetation and cropping seasons. For instance, significantly higher yields were reported under CA plots in sandy soil during dry seasons but significantly lower during wet seasons mainly caused by waterlogging due to excessive precipitation at Chikato village in Zimbabwe (Thierfelder and Wall, 2012). Rusinamhodzi et al. (2011) also demonstrated that 92% of the data showed lower maize yields under a mulch cover practice on a clayey soil under high rainfall, and this effect was attributed to CA increasing soil compaction, which resulted in waterlogging and nutrient immobilization. While Mupangwa et al. (2007) found that maize grain yield was not significantly affected by mulch treatment after two years of mulch application in a sandy soil, at Matopos Research station in Zimbabwe. These results suggest that CA improves yield under dry seasons, while it disadvantages crop performance during wet seasons, regardless of the soil types, suggesting that the benefits of CA on crop yield rely deeply on the specific biophysical conditions.

The benefits of CA are linked to positive improvement of SOC (Gonzalez-Sanchez et al., 2019; Guo et al., 2020), soil quality (Song et al., 2019), decreasing soil erosion and surface water runoff (Fischer et al., 2019) and increasing soil water storage (Sidhu et al., 2019). A study conducted by Edralin et al. (2017) reported that CA improves the profitable production management system, protects natural resources and reduces labour. Their study was carried out under vegetable production with CA involving permanent beds with mulching using dry rice straws while *Crotolaria juncea L.* was used as a cover crop in sandy loam soil. They reported that CA adoption on smallholder farms significantly reduced the manual weeding management by 35% over CT in sandy loam, which in turn reduced labour costs, due to cover cropping and surface mulching by crop residues.

On a saline soil, the combination of reduced tillage and mulching reduced the salt load, which in turn increased crop productivity and profitability of a sorghum-wheat production system (Soni et al., 2021). The use of cover cropping also improved the buildup of SOC and N, (Poeplau and Don, 2015; Cates et al., 2019), and mitigated climate change by lowering the emissions of N₂O and CO₂ (Abdalla et al., 2019). A previous study done by Cates et al. (2019) on the response of SOC on drill-seeded cover crops (rye and bluegrass) under maize production system on a silty loam soil, showed that both cover crops significantly increased the potentially mineralizable carbon (PMC), while bluegrass increased total particulate organic matter (POM). Poeplau and Don (2015) and Abdalla et al. (2019) conducted meta and systematic analysis, respectively which evaluated the SOC sequestration under different cover crops. Poeplau and Don (2015) compiled data from 37 different sites (139 plots) and found that the overall cover cropping significantly improved SOC stock within 22 cm soil depth compared to the control. They demonstrated that the change in SOC stocks ($R^2 = 0.19$) was linearly correlated with time since the crop cover was introduced and SOC stocks improved by 0.08 Mg ha⁻¹yr⁻¹. Abdalla et al. (2019) also demonstrated that the cover crops from legumes ($p < 0.001$; $n = 29$) and non-legumes ($p < 0.001$; $n = 13$) significantly increased SOC sequestration compared to the control treatments. Tadjiev et al. (2023) and Afshar et al. (2019) reported that the adoption of NT decreased land preparation costs by 23% and 27%, respectively compared to a CT system. Both minimum and NT have been reported to significantly reduce total input costs by 16% and 19%, respectively in a paddy-rice production system in Italy (Calcante and Oberti, 2019). Overall, CA reduces negative environmental impacts on soil quality, increases crop yields and reduces input costs addition (Swanepoel et al., 2018).

2.3. Challenges of adoption of conservation agriculture in sub-Saharan Africa (SSA)

In SSA, the predicted population growth of 1.96 billion by 2050 will likely put more pressure on agricultural production (Bongaarts and Casterline, 2013). The pressure on agricultural production may be heavily worsened by climatic variability particularly on sandy soils because of their poor structure and poor water holding capacity. In SSA, CA practice by smallholder farmers is extremely low because of several limiting factors including poor crop residues production for soil surface mulch, lack of equipment for CA such as mechanical CA jab planters, lack of CA training to smallholder farmers and lack of resources to buy herbicides to control weeds in the NT practices at the beginning of CA systems (Araya et al., 2024). In addition to low crop residues production, most crop residues are used for animal fodder either in managed enclosures or stubble grazing during post-harvest (Mazvimavi and Twomlow, 2009). Other CA limiting factors include high-cost management that includes appropriate herbicides for controlling weeds and appropriate fertilizer (Araya et al., 2024). The short duration of most CA studies conducted under smallholder farming limits the potential benefit of adequate (at least 30%) soil surface cover, consequently, limiting soil health and quality enhancement. Vanlauwe et al. (2014) reported that the short implementation of CA practice does not adequately outweigh the higher management costs under CA. Moreover, smallholder farmers mostly believe in an immediate return from their investments in order to maintain their families (Araya et al., 2024) and thus limit the implementation of CA practice by smallholder farmers. Nonetheless, the performance of CA systems can be improved by additional complementary practices such as the addition of appropriate organic and inorganic fertilizers (Vanlauwe et al., 2014), integration of furrow and raised bed tillage systems particularly in a poorly drained vertisols (Araya et al., 2015).

2.4. Effects of conservation agriculture on maize grown on sandy soils

Cereal crops production such as maize are critical staple crops cultivated for food and feed particularly in Africa (Sithole et al., 2016). However, their production is constrained by soil quality degradation, insufficient soil water content and climate change. Climate change, characterized by extreme drought and temperatures, is a primary challenge affecting crop production contributing to environmental factors (FAO, 2010). For example, South Africa (SA) faces significant risks of crop failure due to water scarcity because SA receives a low annual average rainfall of approximately 500 mm (Seckler, 1998). These challenges are particularly

severe on sandy soils where poor management exacerbates this decline of crop production. However, research indicates that CA practices can increase maize yields on sandy soils and under low rainfall regions compared to CT, especially under variable rainfall conditions (Thierfelder et al., 2013; Nyamangara et al., 2014; Chaudhary et al., 2019). The study conducted by Thierfelder et al. (2013) evaluated the response of maize production under CA in sandy loam soil (80% sand) under a mean long-term rainfall of 748 mm yr⁻¹. They found that maize yield production was 75% higher under animal traction rip-line seeding and 91% higher under direct seeded plots compared to CT plots after six growing seasons, and the results could have been further influenced by cotton rotation, which increased water infiltration and soil water content.

A meta-analytical study conducted by Nyamangara et al. (2014), which used 48 CA experiments over 6 years, reported that 59% of the experiments particularly under planting basins significantly increased maize yield compared to CT, but ripper tillage did not outperform CT practice under a semi-arid zone of Zimbabwe. The major soil type in their study area was coarse-grained sand (>70%) characterized by low SOM, soil water retention capacity and low nutrients availability, although some studies were conducted on fertile loams and heavy clay soils. Rusinamhodzi et al. (2011) also conducted a meta-analysis study using a long term (40 years) CA trial and the data demonstrated that CA positively improved maize yield production on sandy soils compared to clayey soils. Another study conducted on a sandy loam soil reported a significantly higher maize grain yield under permanent bed (5.55 t ha⁻¹) and zero tillage (5.49 t ha⁻¹) than under CT (4.81 t ha⁻¹) (Chaudhary et al., 2019). Sithole et al. (2016) reported maize yield increased by 14.6% after two years of NT practice on one of the farms in the North West Province of South Africa, which receives low rainfall (300 – 700 mm annually) with poor distribution.

According to the report by Thierfelder et al. (2015), maize yield production was 80% higher under CA than conventional tillage and also reported a 20% negative effect of CA adoption on maize yield in a loamy to sandy loam soil texture. The authors reported that the negative response of maize yield production on CA adoption could be attributed to a lack of CA experience by smallholder farmers in the initial year of adoption, the slow increase of soil fertility levels and waterlogging during higher rainfall seasons. The adoption of a full CA system significantly increased yield by 9.3% under loamy than sandy soils (Kanthal et al., 2023). Their study concluded that CA can be more effective on loamy soils than sandy soils

because the clay content in loamy soils may have a stronger interaction with SOC which may result in stabilizing SOM and positive response to CA adoption.

Crop rotation also plays a crucial role in improving yield under CA. For example, soyabean-maize rotation increased maize production by 25% compared to silage sorghum-maize rotation in a sandy soil (Da Silva et al., 2020). Maize yield was also higher after soybean production, regardless of tillage practice, suggesting that legume-grass rotations positively influence soil quality compared to grass monoculture (Da Silva et al., 2020). Another study conducted by Phillips (2013) found that maize yield production was higher under maize and soya bean rotation (12.5 t ha^{-1}) than on maize monoculture rotation (11 t ha^{-1}) although the research was conducted in a high rainfall region ($>900 \text{ mm year}^{-1}$) in KwaZulu-Natal Province of South Africa. These findings could be influenced by the improvement of soil quality particularly the enhancement of total N by legumes (Wang and Sainju, 2014; Oliveira et al., 2019). Generally, legumes such as cowpea and soyabean improve total N through biological N fixation (BNF) (Chu et al., 2017). However, the time of planting is very important for soil quality improvement. For example, summer maize grown in winter resulted in decreased yield, consequently limited the increase/recycling of total N, while the cultivation of summer soyabean increased the total N in a sandy soil (da Silva et al., 2020). Therefore, CA practice improves maize yields, but the improvements depend on the site-specific condition and the duration of the CA application.

2.5. Effects of conservation agriculture on soil water content in sandy soils

Crop productivity under rainfed agriculture is strongly influenced by soil water availability in low rainfall regions (Ayman, 2023). Thus, insufficient soil water negatively affects crop production by affecting seed germination, crop growth and yield, in arid and semi-arid regions (Arsyid et al., 2009). According to Ayman (2023), adequate water infiltration and soil water content increases crop yields in semi-arid areas. Dryland, smallholder farmers in arid and semi-arid regions rely on rainfall for crop production and agricultural sustainability. Recently, most African countries including South Africa are facing a serious water scarcity, which is mainly caused by recent recurring severe droughts and the high demand of water with an increasing population (Orimoloye, 2022). Thus, soil water conservation should be prioritized particularly in sandy soils to maintain rainfed agricultural production in areas with low rainfall distribution (Barron et al., 2003). Conservation agriculture improves soil water content by increasing water

infiltration, reducing soil surface runoff and erosion, and reducing the evaporation (Abdallah et al., 2021). The benefits of adopting CA to increase soil water content particularly in sandy soils have been reported by various researchers (Serme et al., 2015; Bekele et al., 2022; Ayman 2023).

No-tillage with sorghum residue retention improved soil water storage capacity by 20% compared to soil under CT in a sandy loam soil (Serme et al., 2015). Ayman (2023), also reported that soil water content increased by 29% and 13% under NT practice compared to cultivated and harrowed lands, respectively in a sandy loam soil. The author stated that the increased soil water content under NT could likely be influenced by the minimal soil disturbance coupled with mulching, which resulted in storing and conserving more soil moisture by reducing water evaporation. McVay et al. (2006) and Fernandez-Ugalde et al. (2009) also found that soil under NT practices have greater water storage capacity than cultivated soils. This is because CA practices improve the build-up of SOC within the soil which alters the distribution of soil pore sizes resulting in improved soil water holding capacity (WHC) which likely increases soil water content (Abdallah et al., 2021). Moreover, the build-up of SOC improves stable soil aggregates which improves water infiltration and minimizes aggregate slaking under rainfall pressures which contributes to runoff and erosion (Murphy, 2015; Abdallah et al., 2019). Murphy (2015) also reported that each 1% increase in SOC was associated to increase in available water in the soil by 2 – 3 mm per 10 cm in a sandy soil.

These results differ from the findings observed by Jabro et al. (2021) who demonstrated a significantly lower soil water content in NT than CT (11.41 and 12.34%, respectively). These findings agreed with the results observed by Obalum et al. (2011) who also found a significant higher soil water content under CT than NT practices with mulch application on both tillage systems in a sandy loam soil. The lower soil water content under NT may be attributed to greater soil compaction under NT systems, which generally exhibit higher soil bulk density compared to CT systems, particularly at the beginning of NT adoption (Villamil et al., 2015). This difference is primarily due to the contrasting soil disturbance regimes i.e. CT involves regular ploughing and tillage operations that disrupt soil aggregates, temporarily loosening the soil and reducing bulk density. In contrast, it eliminates mechanical soil loosening, allowing natural consolidation processes to dominate. Additionally, repeated traffic from heavy equipment used under NT system during planting and harvesting can exert pressure on the soil surface, further increasing compaction. Over time the accumulation of SOM under NT may

enhance aggregate stability and porosity, potentially mitigating compaction; however, this effect is gradual and often insufficient to offset the initial increase in bulk density. For instance, Villamil et al. (2015) reported that NT had higher soil bulk density compared to CT (1.69 and 1.56 g cm⁻³, respectively) within the same year, even when the soil water content was higher under CT than NT systems under maize cropping systems. Conventional tillage reduces soil compaction and creates rough surfaces, which helps limit surface water runoff. In contrast, a literature review on the response of water retention as affected by NT, conducted by Skaalsveen et al. (2019) reported that NT led to poor soil structural properties characterized by increased soil compaction, higher bulk density and reduced soil porosity. This resulted in declining water infiltration and reduced hydraulic conductivity in the soil. However, this review might have reported results from studies conducted across various types of soils, climate and different tillage management systems.

Another study found that reduced tillage namely: planting basins, ripper tine and NT did not significantly affect seasonal soil water content after two years of a study under maize production in both sandy and clayey soils (Mupangwa et al., 2007). Jabro et al. (2016) also reported no significant effects on soil water content under zero tillage, shallow tillage and deep tillage practices after four years of application. These findings suggest that the adoption of NT to improve soil water content may take longer particularly under sandy soil due to low amounts of SOC. In conclusion, the CA benefits on soil water content are mainly attributed to the improvement of water infiltration and the minimal evaporation due to the surface soil mulching by crop residues. The CA system can also lead to a decline in soil water content or may not have a meaningful effect on soil water content in comparison with soils under CT. Therefore, the duration and sites variations contribute to the effects of CA on soil water content in sandy soils.

However, most of the previous scientific results reported on the benefits of CA on soil water content are from the benefits of CA practice under maize production system since this is one of the well-known major cereal crops from smallholder farmers. Thus, there is lack of scientific evidence on the benefits of CA practice under grain sorghum production system particularly in sandy soils in SSA. As a result, the real reflection of how grain sorghum improves soil water under CA systems remain limited to smallholder farmers. The results of this study may strengthen grain sorghum as an ideal crop under climate change in SSA.

2.6. Effects of conservation agriculture on soil organic carbon (SOC) in sandy soils

Sub-Saharan African soils have very low SOC levels which are attributed to prevailing arid, semi-arid and warm climatic conditions. These climatic conditions negatively affect the biomass production of native vegetation which influences the recycling of SOC during the decomposition process (Du Preez et al., 2011). Several studies have shown that the adoption of CA positively improves SOC in sandy soils under different climatic conditions and various cropping systems (Chivenge, 2007; Dou et al., 2008; Villamil et al., 2015). Chivenge (2007) found higher SOC content in a sandy soil under mulch ripping treatment than under CT (6.8 and 4.2 mg g⁻¹ soil, respectively) in a high rainfall region (800 – 1000 mm annually). Similar findings were also observed by Dou et al. (2008) who showed that SOC ranged between 34-37% more in the NT than CT treatments. Villamil et al. (2015) demonstrated that an increase in the amount of crop residue retention under NT significantly improved SOC content within 0-15 cm soil depth in a silty loam soil. These authors concluded that crop residue retention should have played a vital role in increasing SOC concentration during decomposition. According to Dolan et al. (2006), the combination of NT practice with crop residue retention can increase SOC by 30% compared to the combination of CT practice with crop residue retention. Crop residue inputs, with NT, are likely to improve soil aggregates which protect SOC from soil microorganism decomposition (Villamil et al., 2015). Conversely, ploughing breaks down the stability of the soil resulting in exposing protected SOC to rapid mineralization by soil microbes (Curaqueo et al., 2011).

Swanepoel et al. (2018) demonstrated that the CA effects on SOC vary across sites and were also influenced by the nature of soils. Their study investigated the effects of CA on SOC sequestrations in sandy and clayey soils. They reported that SOC was significantly improved under clayey soils while there was no significant difference on SOC between reduced tillage and CT within six to eight years under a maize crop production system in rainfed conditions. These results could be influenced by the poor protection of SOM by sandy soils compared to clayey soils. A medium-term study (7 years) that investigated the benefits of CA on SOC under maize production on a sandy loam soil, found that SOC was significantly increased by 35% at 0-15 cm and 26% at 15-30 cm compared to CT systems (Parihar et al., 2016). Similar results were observed by Bohoussou et al. (2022) with higher SOC within the soil profile under CA compared to CT, because tilling of soil significantly decreased the content of SOC by increasing the decomposition of SOM in the soil (Thomas et al., 2007). In the subsoil under

CA, the absence of soil disturbance supports roots to remain intact which might improve OC inputs (Parihar et al., 2016). Therefore, NT and crop residue retention have positive impacts on the SOC in sandy soils. According to Magdoff and Weil (2004), the long-term adoption of CA provides a long enough time for accumulation of SOM due to the maintenance of crop residue retention.

Soil protein was improved by 13% on sandy loam soils when crop residues were retained on the soil surface compared to plots with crop residue removal in a short-term study (3 years) under rainfed conditions (Singh et al., 2018). These effects of NT, crop residue retention and rotation on soil protein and total SOC could affect aggregate stability and SOC in the different soil aggregate size fractions.

2.7. Effects of conservation agriculture on soil microbial biomass carbon, soil enzyme activities and microbial functional diversity in sandy soils

Soil microbial biomass carbon (MBC) acts as a soil C reservoir, therefore, increasing levels of soil MBC results in increasing the soil C stocks (Dos Santos Cordeiro et al., 2021). Climatic condition is one of the limiting factors on the concentration of soil MBC. For example, Schlöter et al. (2003) reported that the soil MBC declined during summer because of the high temperatures which, resulted in low water content in a study that evaluated the effects of precision agriculture on soil microbial community structure. In sandy soils with low SOC content, high inputs of inorganic fertilizers such as N are often applied to achieve higher crop yield, resulting in negatively affecting soil microbial activity (Dos Santos Cordeiro et al., 2021). For example, the content of soil MBC and soil protein were lower under the highest application of inorganic N (130 kg ha⁻¹) in a sandy soil (Dos Santos Cordeiro et al., 2021). The high levels of application of inorganic N in soils with low SOC content could have led to consumption of native SOM and this was also consistent with the results reported by Liu et al. (2020). Conversely, NT with maintenance of crop residue retention has been linked to increasing soil MBC (Li et al., 2018a). Parihar et al. (2016) demonstrated that maize-based crop rotation increased soil MBC from 45 to 49% within 0 – 30 cm soil depth than CT in a sandy loam soil.

Soil microorganisms and enzymes are fundamental to soil health, playing key roles in soil aggregation (Cerdeira, 2002), hydraulic properties (Pan and Wang, 2009), influence soil

temperature and water transfer (Zhang et al., 2013), and nutrient cycling through the decomposition of organic materials (Waring et al., 2014; De Holanda et al., 2023). Soil enzymatic activities are sensitive indicators of soil quality because they reflect the functioning of soil-ecosystem and they rapidly change if the functioning of the soil is altered (Ciarkowska et al., 2014; Fan et al., 2021). Delelegn et al. (2017) confirmed that different land uses significantly influence soil properties such as soil structure and SOC build-up, which in turn influence soil functioning, and soil microbiome composition. Schlöter et al. (2003) evaluated the response of soil microbial community structure and their functions in N turnover as affected by precision farming in a maize cropping system under two different trials. One of their trials was conducted under <95% of maize yield production while the other trial was under >95% of maize yield production. In their report, the trial under >90% maize yield had soil pH (CaCl₂) of 5.9 under a loamy soil while under <90% maize yield trial, soil pH (CaCl₂) was 6.1 on a silty loam soil. Thus, the soil microbial communities were affected by seasonal changes of agroecosystems and also reported that soil MBC declined during the summer season which could be attributed to the extreme dryness and hot temperature events in southern Germany (Schlöter et al., 2003). The community structure composition and activities of soil microorganisms are also affected by the climatic conditions. A previous study conducted by Borowik and Wyszowska (2016) reported that the activity of dehydrogenase was highest between 10 – 15 °C suggesting that temperatures beyond such thresholds could have negatively affected the different mechanisms of the soil microbes. A pot experiments conducted by Siebielec et al. (2020) found that dehydrogenases and phosphatases were three times significantly lower under drought stress compared to control treatments in a sandy soil with 1% clay content in Poland. Thus, CA should be encouraged particularly in sandy soils to moderate the negative impact of climate on soil health and improve SOC concentration which may likely increase soil microbial community and functions.

Several studies have demonstrated that CA improves soil enzyme activities in sandy soil (Melero et al., 2009; Parihar et al., 2016; Chaudhary et al., 2017). Melero et al. (2009) evaluated the short- and long-term effects of CA on soil enzymatic activities (dehydrogenase and B-glucosidase) under a sandy clay loam soil. They found that CA improved the activity of dehydrogenase and β -glucosidase in the topsoil than soils under CT in both short- and long-term studies. Conservation agriculture, particularly permanent raised beds increased the activity of dehydrogenase by 49 and 50% within 0-5 and 5-15 cm soil depth, respectively compared to CT in a maize-based crop rotation, sandy loam soil, in a long-term study

conducted by Chaudhary et al. (2017). Similarly, Parihar et al. (2016) observed significantly greater activities of alkaline phosphatase, β -glucosidase, dehydrogenase and fluorescein diacetate under CA than plots under CT.

Thus, the retention of crop residues influences the activity of soil microorganisms since they break down organic materials and use this as food for energy. A meta-analysis study that evaluated the response of soil enzyme activities on CA adoption across the world concluded that CA adoption is important for enhancing soil enzyme activities as well as the combination of NT with crop residues, offers great potential and promise for improving soil enzyme activities (Wen et al., 2023). Furthermore, the adoption of NT with crop residues increased the Shannon index (H), Simpson's Dominance index (D) and McIntosh index (U) in a 3-year study on a sandy loam soil (Dai et al., 2017). However, their study demonstrated that 50% of the application of crop residues had higher enhancement of soil microbial functional diversity than 100% application of the crop residues. This suggests that too much residue retention on the soil surface can create poor soil conditions which can reduce soil microbial activities. Another study that evaluated the response of soil microbial functional diversity as affected by vegetation restoration reported a significant increase in the Shannon index (H), microbial evenness (E) and Simpson's Dominance index (D) compared to degraded sandy soil (Zhang et al., 2013). Their study concluded that the conservation of sandy soil through vegetation restoration improves soil microbial metabolic activity and functional diversity in sandy soils.

The effects of the grain sorghum production under CA systems could benefit more on the soil MBC, soil enzymatic activities and soil microbial community functional diversity compared to the mostly used cereal crops such as maize due to the superior morphological adaptation, physiological responses and biochemical mechanisms sorghum has compared to maize and other cereal crops. Such scientific results are limited to farmers due to lack of knowledge and comprehensive evidence to rely on. This study is crucial to provide a comprehensive evidence on how grain sorghum influences the activities of soil enzymes and microbial community functional diversity in sandy soils under CA.

2.8. Effects of conservation agriculture on soil fertility under sorghum/maize production in sandy soils

Soil quality degradation is amongst one of the primary limiting factors for crop yield production, consequently affecting long-term agricultural sustainability, particularly in sandy soils. Because of the poor water holding capacity in sandy soils, nutrients are likely to be leached away during heavy rains and consequently affect soil functioning. Conservation agriculture can improve some of the major soil functions including C cycling and transformation, the recycling of nutrients, soil structural maintenance and soil biodiversity conservation (Carceles et al., 2022). According to Malobane et al. (2018), the three principles of CA namely: reduced tillage, mulch and crop rotation influence soil quality differently. For instance, soil cover improves soil quality by minimizing soil erosion, improving water and nutrient holding capacity and enhances soil C sequestration (Busari et al., 2015; Koudahe et al., 2022). Minimal ploughing enhances the stability of the soil, water infiltration, soil aeration, and SOM by maintaining more crop residue retention and improves soil microbial activities by creating a stable environment for soil organisms (Busari et al., 2015). Hobbs et al. (2008) observed that the combination of the CA principles significantly reduces the costs of inputs and results in a sustainable production system. However, CA systems affect soil quality differently across sites following the differences of site-specific factors like types of soil, climatic conditions, types of cover crops, crop rotation and the duration under CA operating systems (Indoria et al., 2017; Hermans et al., 2021). For example, during the dry seasons, CA might be more beneficial on sandy soils than clayey soils because sandy soils have poor water retention capacity, while clayey soils are less affected by rainfall fluctuations (Clark, 2024).

The retention of crop residues with residues containing high recalcitrance caused by the lignin content results in slow deposition rates and that leads to slow building up of soil structural stability particularly in sandy soils (Mafongoya et al., 1998; Abiven et al., 2008). The retention of crop residues such as legumes containing high ash alkalinity and N will likely have a significant effect on soil pH than residues with lower ash alkalinity such as wheat (Xu and Covently, 2003). Despite the different types of crop residues, most literature demonstrated that the retention of these crop residues coupled with minimal soil disturbance plays a positive crucial role in improving soil quality in sandy soils.

The application of soil mulching improved soil N, P and K content compared to no mulch application on a sandy loam soil under sorghum-wheat production system (Soni et al., 2021). Malobane et al. (2020) also observed similar results where 30% of crop residue retention where it was reported that it increased the availability of P, Mg, K, Ca) and CEC by 4 to 32%

compared to plots where crop residues were removed in a sandy clay loam soil over the short-term. They found that NT improved total N, total organic N (TON), Mg and Na by 3.19 to 45% than under CT under sweet sorghum production on sandy clay loam soil and semi-arid climatic condition. In this study, the retention of crop residues was the main driver of soil quality enhancement which is attributed to the increased activities of soil microbes which are responsible for breaking down soil SOM while recycling soil nutrients. A previous research reported an increase of total N and available P while soil pH, extractable K were moderated in less than three years of the CA practice on a sandy clay loam soil (Mloza-Banda et al., 2014). Da Silva et al. (2020) demonstrated that in the rotation of growing soyabean after maize production system under NT resulted in increased total N compared to maize monoculture systems.

Overall, according to the literature, a CA system has positive benefits on soil fertility. However, the enhancement of soil properties following CA treatment mainly relies on the initial SOC within the soil as well as the climate (Page et al., 2020). In sandy soils, the changes in soil properties may take longer because of the low SOC content than on clayey soils (Godde et al., 2016). This suggests that longer term practice of CA may be required in soil types to fully observe meaningful CA benefits on soil quality (Malobane et al., 2020). Overall, the adoption of CA systems will likely improve the quality of sandy soils, particularly to the smallholder farmers who are financially disadvantaged to maintain agricultural sustainability over the long-term. However, the effects could be more dependent on climatic conditions, soil properties (particularly texture and SOC), crop types and management.

2.9. Sorghum as a climate-smart crop

The sustainability of sorghum under extreme climatic stresses such as low rainfall distribution and prolonged drought, enhances food security for many developing countries. Sorghum is drought and heat tolerant and can grow under barren and saline-alkaline soils (Vasilakoglou et al., 2011; Wu et al., 2024). It performs well under arid and semi-arid regions because it has well developed root system, leaves are well protected by wax and the leaves roll themselves up under extreme climatic stresses (Rooney and Waniska, 2000; Hadebe et al., 2017a). Currently, sorghum is the fifth highest produced cereal crop, following maize, wheat, rice and barley (FAO, 2017). It is used for various purposes including, bio-fuel production, animal feed/fodder, beer production and in food production like as bread, soft and thick porridges (Malobane et al.,

2018; Dunjana et al., 2022). Sorghum is highly nutritious and contains a health beneficial phenolic compound with antioxidant activity than other cereal crops (Xiong et al., 2019). Thus, the consumption of sorghum may likely improve gut health and minimizes the risks of chronic diseases (Xiong et al., 2019).

Apart from the benefit of sorghum on human health and consumption, sorghum production may likely enhance soil quality under CA practices (Malobane et al., 2018). For instance, the production of sorghum biomass promoted the recycling of soil nutrients through decomposition process after sorghum residues were retained. A previous study conducted under extreme temperatures in sandy soils of Brazil reported that sorghum yield production was 100% higher after the adoption of NT practice than under CT practice (Da Silva et al., 2020). The authors demonstrated that the improvement of sorghum yield could be influenced by the enhancement of total N content which was improved by the combination of NT practice and cover cropping during the study period. A two-year study on sandy loam soils in southern zone of Burkina Faso (mean rainfall of 900 mm yr⁻¹) demonstrated that NT increased sorghum yield by 1.39% compared to CT (Serme et al., 2015). The authors demonstrated that higher sorghum yield obtained under zero tillage was influenced by the improvement of soil water content with the mean weekly soil water content of between 44.15 – 53.66 mm over a 12-week period and soil structure after the two consecutive seasons of the practice of NT practices. However, the benefits of NT are not always immediate.

In the early stages of adoption, CT may outperform NT. For instance, in the first year of NT adoption, CT had 29% higher sorghum yield than NT in the study conducted by Serme et al. (2015). Similarly, lower sorghum grain yield was observed in the NT treatment than in the chisel ploughing (>28%) and CT (>28%) treatments in year two of the study conducted by Ayman (2023). Tesfahunegn (2012) also reported lower sorghum grain yield under NT than tilled lands, highlighting that the yield benefits of NT often emerge over time as soil conditions improve (Ogle et al., 2012). Moreover, in the early stages of NT adoption, weeds highly compete with crops for nutrients which negatively affect crop growth. Therefore, because of crop production decline or failure under climate change, farmers may have to shift and focus on the production of sorghum because of its tolerance to drought.

Sorghum is increasingly recognized as a climate-smart crop due to its exceptional tolerance to drought and heat stress, traits that are critical under projected climate change scenarios.

According to Ringler et al. (2010), sorghum yield is expected to slightly increase under projected climate change scenarios while yields of other major cereal crops such as maize, rice and wheat are projected to decline. This resilience is largely attributed to sorghum's ability to maintain key physiological processes including photosynthesis under drought stress, a capacity that maize and wheat lack (Hadebe et al., 2017a). Furthermore, sorghum exhibits several adaptive traits such as delayed leaf senescence, high chlorophyll content, low canopy temperature and superior all of which enhance its performance under drought stress transpiration efficiency. The need for more food, under arid and semi-arid conditions, coupled with climate change, will result in the use of vulnerable sandy soils. Moreover, sorghum may likely increase the soil fertility levels due to higher and more resistant crop biomass production when integrated with CA principles under harsh climatic conditions. The effects of sorghum-based CA under semi-arid conditions, on sandy soils, on crop yield, soil water content and soil quality need to be clearly understood if the practice it to be sustainable.

2.10. Summary

Conservation agriculture is a highly promising and environmentally friendly agricultural practice for improving soil quality and increasing crop yield especially in fragile sandy soils particularly under marginal lands through its effects on SOC, infiltration, soil water content and soil microbial community ecosystems. The improvement of crop yield under CA is associated with the enhancement of soil water content, especially on sandy soils, due to surface crop residue retention which minimise evaporation. Crop rotation systems positively improve crop yield by increasing total N within the soil and protecting crops against pests and diseases. When NT is combined with crop residue retention, soil water content is improved on sandy soils by minimising evaporation and by improving water infiltration through soil structure enhancement during decomposition of surface crop residues retention. Conservation agriculture improves SOC, which enhances the distribution of soil pores, resulting in higher water holding capacity of sandy soils. The use of sorghum as a climate smart crop may likely improve soil quality of sandy soils and grain yield under CA practice in arid and semi-arid regions. Overall, CA improves soil quality, increases crop yields, soil water content and reduces production costs in sandy soils.

2.11. Research gaps

- i. There is paucity of scientific evidence on the yield and soil water content benefits of sorghum based-CA practices under rainfed conditions in semi-arid smallholder farms, on sandy soils, in South Africa.
- ii. There is paucity of comprehensive evidence of the impact of the combination of sorghum-based CA adoption and planting date in semi-arid farming systems on soil microbiological activity in sandy soils of South Africa.
- iii. Little information has been reported on the relationship between SOC fractions and sorghum-based CA practices in sandy soils under semi-arid rainfall regions in South Africa.

CHAPTER THREE

3.0. SHORT-TERM TILLAGE MANAGEMENT EFFECTS ON GRAIN SORGHUM GROWTH, YIELD AND SELECTED PROPERTIES OF SANDY SOILS IN TWO CONTRASTING CLIMATIC CONDITIONS, SOUTH AFRICA

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3.1. Abstract

Poor soil fertility and water holding capacity, coupled with climate change, threaten smallholder agriculture under dryland conditions, particularly on sandy soils. The resilience of sorghum makes it an ideal candidate crop for conservation agriculture (CA), under these conditions, but its productivity and effectiveness could depend on the cultivar used, planting time, tillage, and rotation. This study determined the effects of these factors on selected soil properties, growth and grain yield of two sorghum cultivars on sandy soils, under semi-arid and sub-humid conditions. The trial was conducted on sandy soils with <10% clay and <1.0% SOC, between 2020 and 2023 at Mphanama village (Limpopo Province) and between 2019 and 2022 at Clau-Clau village (Mpumalanga Province), South Africa. The experiment had a randomized complete block design (RCBD) set up, in a strip-split-split-plot treatment structure with three replications. The treatment factors were tillage (conventional tillage (CT) and no-till (NT)), planting date (early and late), and rotation (with cowpea or sorghum monoculture) and sorghum cultivar (Pan 8816 and Macia). At Mphanama, early planted sorghum resulted in significantly taller plants (101 cm) than late planted crop (91.0 cm) in season three. Early planted sorghum also outperformed the late planted crop, with 44.4% greater height and 36.1% higher 1000-seed weight (TSW) in the second growing season at Clau-Clau. Furthermore, the grain yield (1.33 and 0.56 t ha⁻¹, respectively) and dry matter yield (2.38 and 1.10 t ha⁻¹, respectively) were significantly higher for early than late planting in season two at Clau-Clau. At Mphanama, the early planted sorghum under NT (1.79 t ha⁻¹) had a significantly higher

grain yield than early planted sorghum under CT (0.93 t ha^{-1}) and late planted sorghum under NT (0.88 t ha^{-1}). Early planted sorghum had a greater 1000 seeds weight (26.9 g) than late planted sorghum (22.70 g) at Mphanama. The NT treatment had significantly higher soil available P and exchangeable K than the CT treatment in season two at Clau-Clau. Early planting had 30.4% higher exchangeable K than late planting, while NT increased total N by 50% relative to CT, in season three at Clau-Clau. At Mphanama, late planting had 14.3% higher exchangeable Ca and 16.8% higher exchangeable Mg than early planting in season two. No-till had significantly higher soil available P by 24.5%, and lower exchangeable Ca by 10.3%, compared to CT treatment in season two at Mphanama. Late planting increased exchangeable Ca and Mg by 18.3% and 22.0%, respectively, compared to early planting in season three at Mphanama. The findings of this study show the positive effects of early planting and NT on sorghum grain and dry matter yields were greater during the season with higher rainfall, while effects on soil properties were greater in a drier season, with no cultivar and rotation effects on these infertile sandy soils.

Keywords: Conventional tillage, cultivar, no-tillage, planting date, rotation.

3.2. Introduction

The sustainability of crop production in Africa is threatened by multiple challenges such as low soil fertility, poor management strategies, and extreme weather events, due to climate change (Njoloma et al., 2016; Malobane et al., 2020; Dunjana et al., 2022). Increasing demand for food, feed, fibre and energy production, has led to the expansion of cultivation onto marginal land, including sandy soils. These soils are characterised by low SOC content, limited CEC, and poor soil water retention (Huang and Hartemink, 2020). The low fertility and poor water holding capacity of sandy soils limit crop productivity. Climate change amplifies these challenges, posing a severe threat to sustainable crop production for many smallholder farmers in Africa, who continue to attain low yields. Prolonged droughts associated with climate change intensify water scarcity, this significantly affecting crop production. Additionally, extreme weather events, including unexpected storms, accelerate nutrient depletion from agricultural soils through runoff and erosion, thus exacerbating soil fertility decline.

Conventional tillage (CT), which is commonly practised by smallholder farmers, enhances runoff and erosion, exacerbating nutrient losses particularly in sandy soils, consequently hampering crop production. Ekwue and Harrilal (2010) reported that sandy soils experienced 87.6% greater soil loss compared to clayey loam soils resulting in reduced crop yields. This soil degradation, coupled with the impacts of climate change, poses significant challenges to agricultural productivity in SSA. Projections suggest a 3.2% decline in cereal crop production by 2050 due to climate change (Hadebe et al., 2017a). However, the adoption of climate-resilient agricultural practices that can improve soil quality, water availability, mitigate erosion and improve SOM can contribute to the sustainability of crop production in regions with sandy soils (Rahman et al., 2008; Kraft et al., 2012).

Conservation agriculture has a potential to enhance soil quality on sandy soils in marginal areas. By reducing soil disturbance, retaining crop residues as mulch and crop rotation, CA enhances soil nutrient cycling (Dube et al., 2012; Busari et al., 2015), improves soil water storage and minimises greenhouse gas emission (Malobane et al., 2020). The retention of crop residues improves the SOC concentration and enhances soil structure and nutrient cycling. However, this effect depends on the quality of the crop residues (C/N, lignin, polyphenols etc), which governs the rate of decomposition (Malobane et al., 2020). The rotation of cereals with legume crops, such as cowpea, could enhance soil fertility status through biological N fixation. However, even greater benefits can be obtained by coupling CA with drought-tolerant cereal crops such as sorghum that offer stable yields in arid and semi-arid climates.

Sorghum has received renewed interest from researchers due to its ability to withstand drought and other extreme climatic conditions (Rao et al., 2011; Malobane et al., 2020; Dunjana et al., 2022). This crop (sorghum) is the fifth most important cereal crop in the world after rice, wheat, corn/maize and barley, and is mostly cultivated for grain for human and animal consumption and bioenergy production in arid and semi-arid tropical regions including Africa (Ramatoulaye et al., 2016). Sorghum can contribute to household food security and secure livelihoods in marginal areas of South Africa (Dunjana et al., 2022). The leaves of this crop are well protected by a waxy cuticle and roll-up to minimize transpiration during drought periods, while the crop becomes dormant when drought continues (Ramatoulaye et al., 2016). While several researchers have worked on sweet sorghum (Cosentino et al., 2012; Rao et al., 2011; Malobane et al., 2020), there is limited knowledge about the performance of grain sorghum under CA in South Africa, especially on sandy soils under smallholder agriculture.

Malobane et al. (2018), showed that the adoption of CA can increase sweet sorghum yields in drought-prone areas of South Africa. This therefore highlights the potential of sorghum for smallholder farmers who are largely located in dry areas. However, yield could depend on both the cultivar and cropping systems. Therefore, identifying suitable cropping systems that will foster resilience to climate change and improve the quality of sandy soils particularly in arid and semi-arid areas of South Africa, is crucial. Conservation agricultural practices and knowledge of appropriate sorghum cultivars, planting date and rotation could contribute to this goal.

The implementation of CA has the potential to improve soil structure, enhance nutrient availability, and increase soil water retention, leading to enhanced soil health and increased productivity particularly in poor soils, such as sandy soils. However, some studies have reported conflicting findings on the effects of CA on sandy soils (Lasisi and Aluko, 2009; Mchunu et al., 2011; Da Silva et al., 2020). For example, Da Silva et al. (2020) observed a 6% increase in soyabean yields under NT compared to CT on sandy soils. In contrast, Lasisi and Aluko (2009) reported a higher yield on CT than NT plots on similar soil types. These conflicting findings necessitates more research to elucidate the effects of CA on the performance of different sorghum cultivars on sandy soils on contrasting sites.

This study investigated the effects of planting date, tillage, and crop rotation on the growth, dry matter, yield of two sorghum cultivars, and selected soil properties on sandy soils under sub-tropical semi-arid conditions. By studying these factors, this study aimed to provide valuable insights into the adaptability and performance of different sorghum cultivars and CA practices. Overall, this study is important for smallholder farmers in regions with sandy soils, as it aims to provide evidence-based recommendations for improving crop yields, enhancing soil health, and building resilience to climate change. By identifying the most effective combination of CA practices, sorghum cultivars, and planting dates, farmers can optimize their agricultural production and enhance soil health and build resilience to climate change.

3.3. Materials and Methods

3.3.1. Site description

This study was conducted at Mphanama village (2021/22 – 2022/23) and Clau-Clau village (2020/21 – 2021/22) in Limpopo and Mpumalanga Provinces, respectively, South Africa (Figure 3.1). Mphanama (24°35'25,938"S; 29°51'33,948"E) is under Sekhukhune District Municipality and about 108 km south-east of Polokwane (Phakoago, 2017). According to Mphandeli et al. (2015), Mphanama village is within the Bushveld ecoregion and has a semi-arid climate. The average annual rainfall at Mphanama is approximately 560 mm (Mphandeli et al., 2015) with a mean temperature of 22 °C (Nzuza et al., 2021). The soils at Mphanama study site were derived from unconsolidated alluvium parent materials and are of the Oakleaf soil form (South African soil classification system) with reddish-brown topsoil, aluvic red apedal subsoils, weak silica cementation and it is equivalent to Chromic Cambisol (FAO) (Van Huyssteen, 2020). Clau-Clau village (25°21'47,514"S; 31°12'35,64"E) falls under Mbombela Local Municipality, with a sub-humid climate and receives an annual mean rainfall of approximately 748 mm, which occurs between November and February (Murovhi et al., 2012). The annual average minimum and maximum temperatures range between 14 °C and 28 °C, but the extreme lowest and highest recorded daily temperatures ranged between -2.0 °C and 41.7 °C, respectively (Paterson, 2012). Clau-Clau has Fernwood soil form (South African soil classification system) with the topsoil dominated by grey to grey-brown sandy and yellowish-brown sandy soils in the subsoil. Fernwood is equivalent to Hyperdystric Stagnic Regosols (FAO) (Van Huyssteen, 2020). These soils were formed from unconsolidated alluvium parent materials.

At Mphanama, sorghum has been grown annually, while maize was grown annually at Clau-Clau, both under CT. Temperature and rainfall conditions for both study sites are shown in Figures 3.2 and 3.3, respectively. At both sites, temperature was almost constant from October to March and then gradually decreased until July (Figure 3.2), with variable rainfall through the experimental period. At Mphanama, the highest rainfall was received in December with the second growing season (2021/22) having higher rainfall than the third season and long-term average (Figure 3.3A). Precipitation increased from October to January with higher rainfall experienced in the third growing season compared to the second and the long-term average at Clau-Clau (Figure 3.3B). Generally, Clau-Clau received higher rainfall and lower temperature than Mphanama. In season one, the entire experimental field was ploughed before applying the treatments. Crop residues produced from the first season were then used to cover the soil under NT in the second season. Therefore, the results section of this study presents data from the second and third growing seasons, after the treatments were implemented. During the second

season, when legume rotation was introduced, sorghum growth parameters and yield were measured only in plots where sorghum was planted.

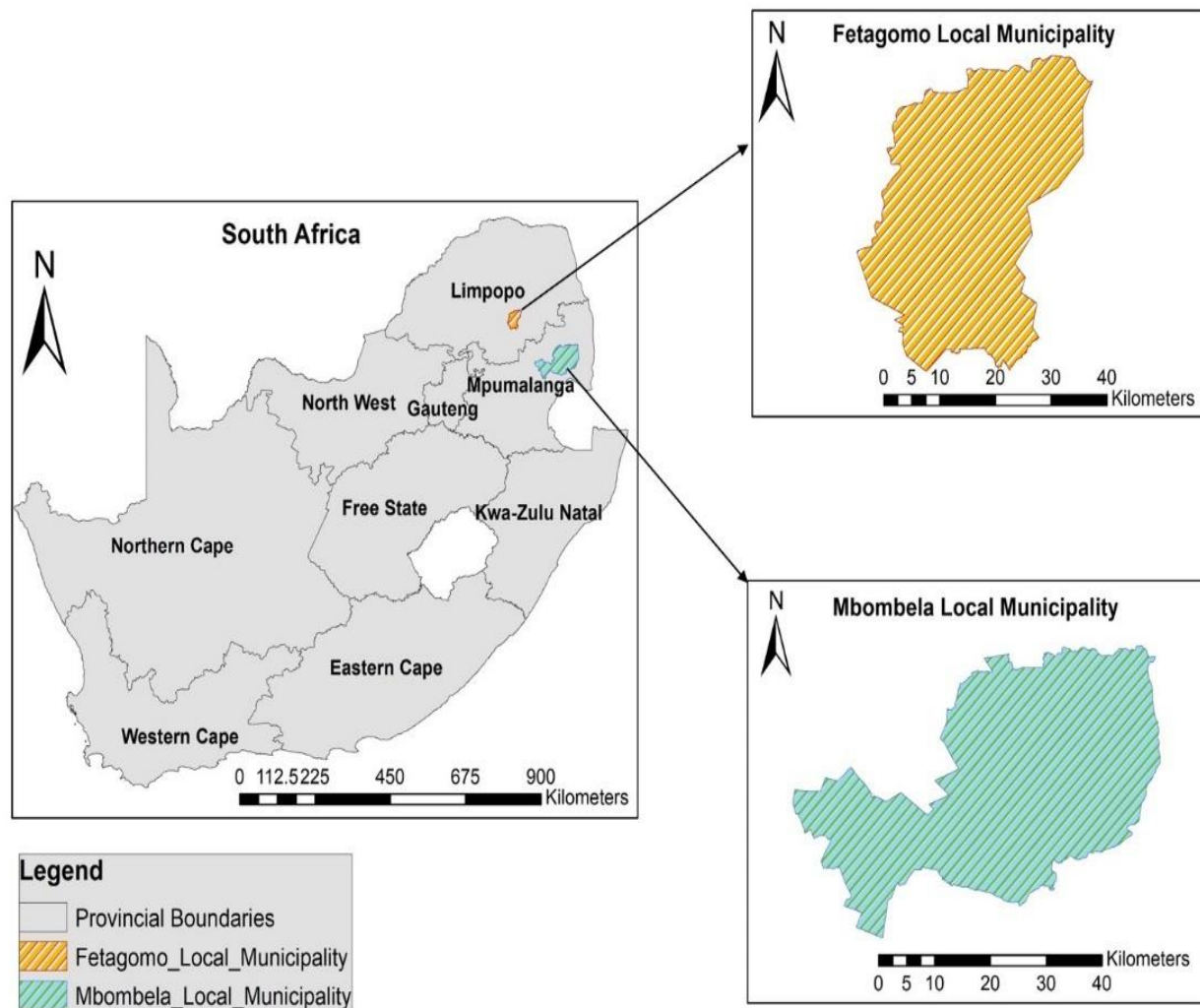
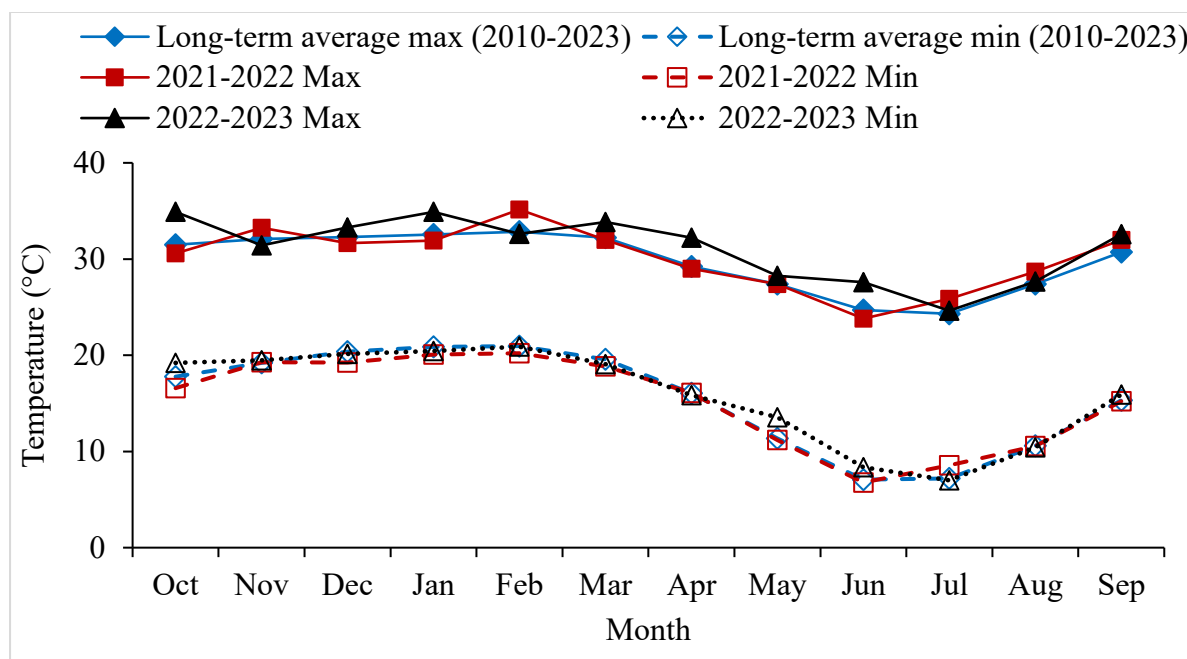


Figure 3.1: South African map showing the two selected study sites as reported by their local municipalities (Map created by Arc GIS).

A



B

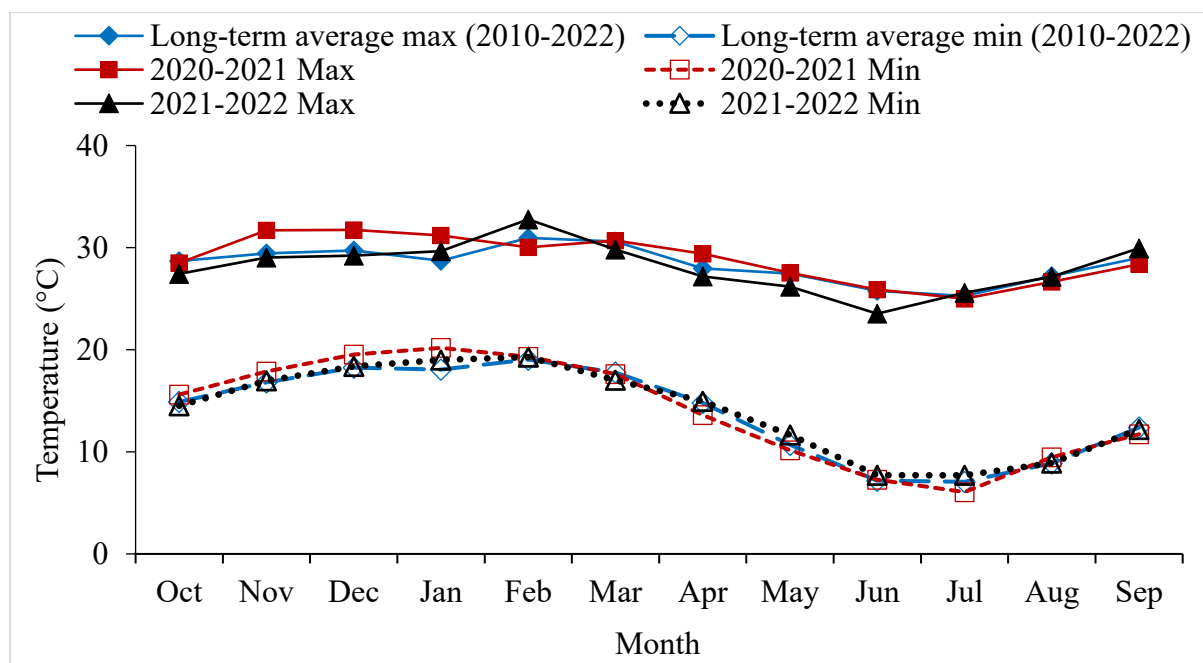
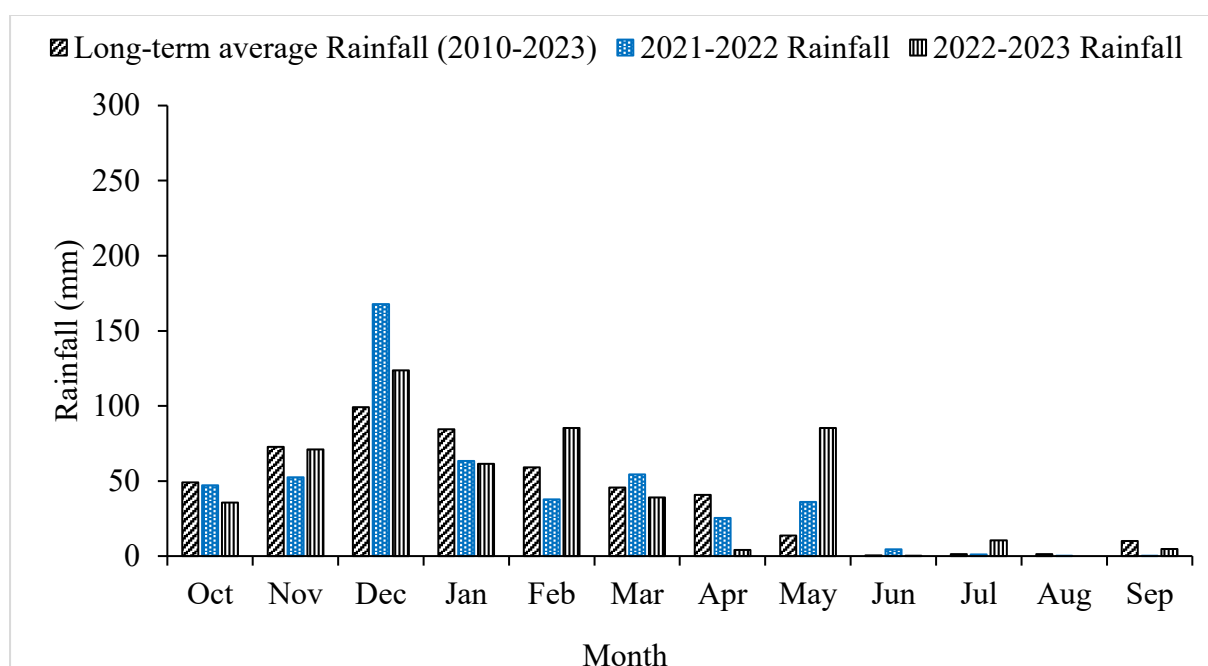


Figure 3.2: Long-term and seasonal temperature conditions. A: Long-term (2010 – 2023); 2021 – 2022; and 2022 – 2023 temperature conditions at Mphanama (Data from station 0677802BX, Polokwane). B: Long-term (2010-2022); 2020 – 2021; and 2021 – 2022 temperature conditions at Clau-Clau (Data from station 0555750 9, Nelspruit).

A



B

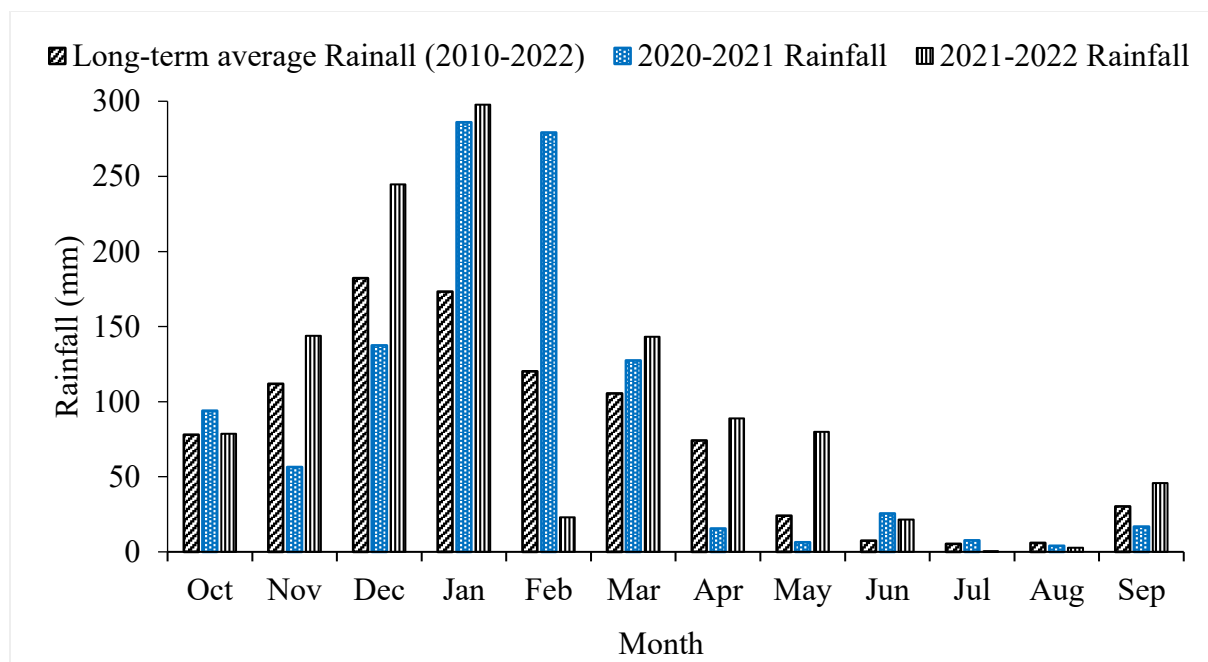


Figure 3.3: Long-term and seasonal rainfall conditions. A: Long-term (2010 – 2023); 2021 – 2022; and 2022 – 2023 rainfall conditions at Mphanama (Data from station 0677802BX, Polokwane). B: Long-term (2010-2022), 2020 – 2021; and 2021 – 2022 rainfall conditions at Clau-Clau (Data from station 0555750 9, Nelspruit).

3.3.2. Experimental design

The experiment was carried out in randomized complete block design with a strip-split-split-plot treatment structure, replicated three times (Gomez and Gomez, 1984). Planting date (early and late) and tillage system were assigned to the horizontal and vertically arranged main strips, respectively (Figure 3.4). Early planting was done in the first week of December, whilst late planting was done in the second week of January in every growing season. The two tillage systems were conventional tillage (CT) with crop residue removal and no-till (NT) with crop residue retention. This vertical-horizontal split plots gave intersection plots, which were split into two and assigned to the two crop rotations i.e. sorghum-sorghum-sorghum (S-S-S) and sorghum-cowpea-sorghum (S-C-S). The rotations were divided in two to accommodate the two selected cultivars i.e. Pan 8816 and Macia. These cultivars are known to have the ability to tolerate dry weather condition and are characterized by low tannin and are semi-dwarf hybrids. The experiment consisted of 16 treatments with three replicates, which resulted in 48 experimental plots of 6 x 4.5 m in size, with 1 m borders between plots. The experiment was conducted across three growing seasons, between 2019/20 – 2021/22 at Clau-Clau, and between 2020/21 – 2022/23 at Mphanama, with the first season being devoted to produce residues that were required to go with NT.

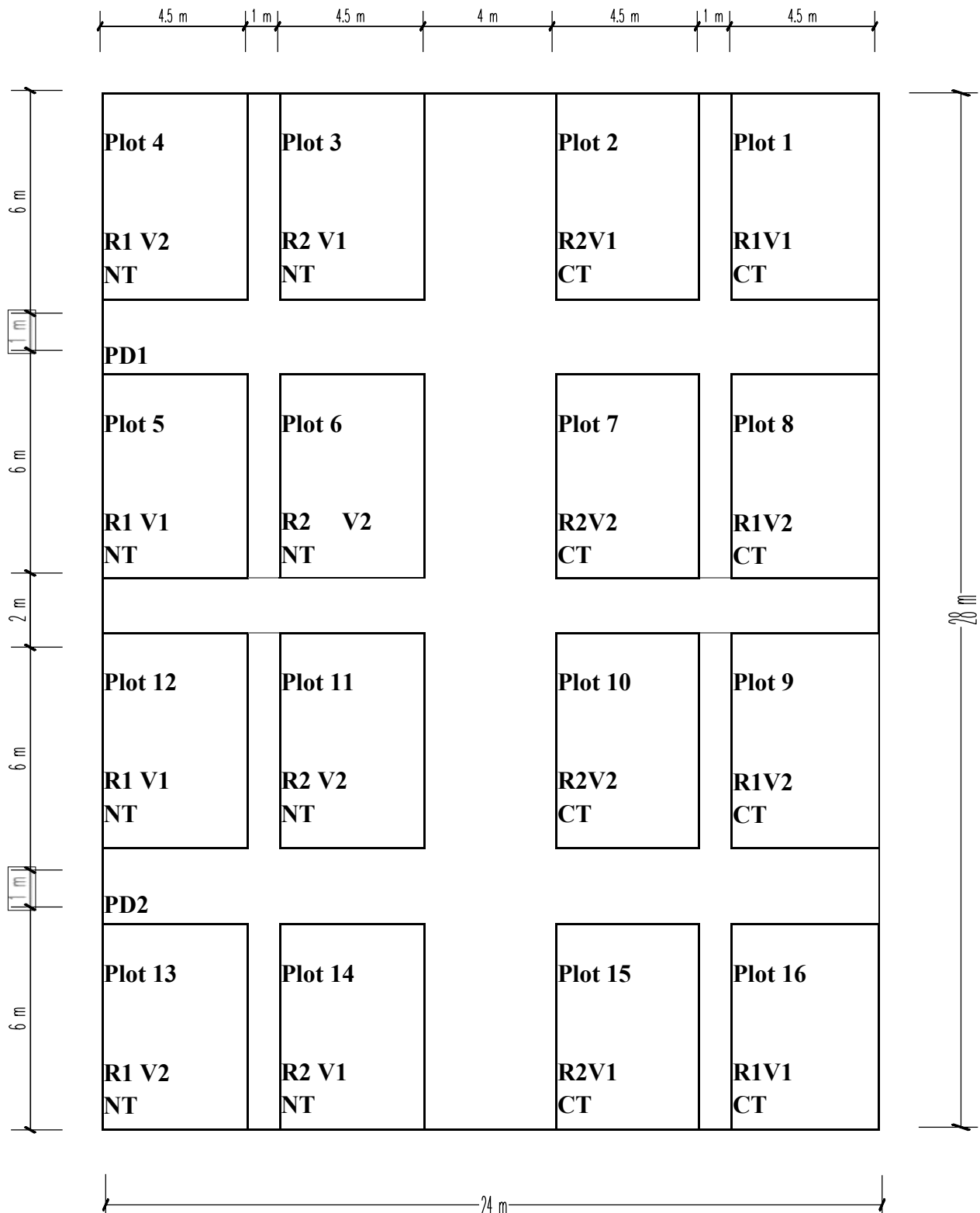


Figure 3.4: Trial layout showing one replicate. PD1 and PD2 – early planting date and late planting date, respectively; NT and CT – No-tillage and conventional tillage, respectively; R1 and R2 – sorghum-cowpea-sorghum and sorghum-sorghum-sorghum, respectively; V1 and V2 – Pan8816 and Macia cultivars, respectively.

3.3.3. The management of non-experimental variables

The entire experimental field was ploughed with a mouldboard plough and harrowed to breakdown large clods to make a fine tilth at the onset of the experiment in 2019 at Clau-Clau and 2020 at Mphanama, marking the first growing season. The second (with the rotation of cowpea in some plots) and third (sorghum only) growing seasons were 2020/2021 and 2021/2022, respectively for Clau-Clau village and in 2021/2022 and 2022/2023, respectively, for Mphanama village. Crop residue retention was only applied on the NT plots after each harvest whereas the CT plots were left bare (crop residues removal) throughout the experimental period. The CT plots were ploughed to a depth of approximately 30 cm at the beginning of each growing season using a tractor-drawn mouldboard plough and harrowed with a tractor-drawn disc plough. In both CT and NT plots, hand hoes were used to open rows for planting. To ensure optimal nutrient levels, fertilizer was applied based on the initial soil analysis. Monoammonium Phosphate (MAP) fertilizer (218 kg ha^{-1}) was applied at planting to supply N (24 kg ha^{-1}) and P (48 kg ha^{-1}) while Limestone Ammonium Nitrate (LAN) fertilizer (259 kg ha^{-1}) was applied as top-dressing after six weeks of planting to supply an additional $72.5 \text{ kg N ha}^{-1}$. Glyphosate (N-(phosphono-methyl) glycine, 360 g L^{-1}) was used to kill the weeds in all plots after harvest and before the next growing season. Cylam 50 EC (Lambda-cyhalothrin (pyrethroid), 50 g L^{-1}) was used to control pests in the grain sorghum crops. Sorghomil Gold (600 SC) was used to control weeds in all the NT plots whereas hand hoes were used to remove weeds in the CT plots. The study was conducted under rainfed conditions (depended on rainfall).

3.3.4. Soil sampling and analysis

Three soil subsamples were collected randomly before and after each harvest using a soil auger at 0 – 30 cm depth in each experimental plot, and were mixed to make a composite sample, making a total of 48 samples from the 48 plots. The samples were air-dried and sieved ($<2 \text{ mm}$) before soil analysis. Soil pH (H_2O) and electrical conductivity (EC) were measured at 1:2.5 soil: water ratio (Okalebo et al. 2002). Soil organic carbon (SOC) was determined following the Walkely-Black method (Combs and Nathan 1998). Soil particle size distribution was determined following the hydrometer method, after dispersion with 1 M sodium hexametaphosphate (Nelson and Sommers, 1996). Total N (TN) was determined following the dry combustion method using the Flash 2000 organic Elemental Analyzer (Milan, Italy). Soil

available P was determined following the P-Bray 1 method (Kuo, 1996). Exchangeable Ca, K and Mg were determined by the ammonium acetate method (Sumner and Miller, 1996). The initial soil properties are presented in Table 3.1.

Table 3.1: Initial soil properties at Mphanama and Clau-Clau villages

Parameters	Mphanama	Clau-Clau
pH (H ₂ O)	8.35	5.57
EC (mS m ⁻¹)	8.25	0.97
P (mg kg ⁻¹)	68.6	7.6
K (mg kg ⁻¹)	285	16
Ca (mg kg ⁻¹)	3610	57
Mg (mg kg ⁻¹)	136	20
Total N (%)	0.07	0.05
SOC (%)	0.45	0.39
Sand (%)	92	88
Silt (%)	2.0	4.0
Clay (%)	6.0	8.0
Textural Class	Sand	Sand

Note: pH (H₂O) – pH measured in water; EC – electrical conductivity; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium; N – total nitrogen; SOC – soil organic carbon.

3.3.5. Sorghum growth and dry matter yield

Plant measurements included plant height, grain yield, TSW and above ground dry matter yield. Plant height was measured using a tape measure from the base to the tip of the plants at the harvest stage. Grain yield was harvested from a net plot measuring 2.5 m × 4 m. The

harvested grain was then threshed, weighed and expressed as t ha^{-1} . To determine the average weight of individual seeds, 1000 seeds were weighed, replicated three times and this weight was reported as TSW in grams. The above ground dry matter was also determined from the net plot, by harvesting sorghum biomass after harvesting of the panicles at the end of the season, drying in an oven at 60°C for 48 hours, and weighed and the results were expressed as t ha^{-1} . Only sorghum biomass was measured in this study because the legume biomass got affected by extreme temperatures. The results section of this study presents data from the second and third growing seasons, after the treatments were implemented at Mphanama (2021-2022 and 2022-2023, respectively) and at Clau-Clau (2020-2021 and 2021-2022, respectively). However, At Mphanama, only the results for season three (2022/23) on the sorghum growth parameters are presented, due to crop failure as affected by severe drought and lack of precipitation during the second growing season. The results for soil properties excluded the effects of sorghum cultivars due to no significant difference in all measured crop growth parameters.

3.3.6. Statistical analysis

Analysis of variance (ANOVA) was performed using JMP 16 statistical package software (SAS, 2021) to assess the effects of tillage, planting date, cultivar and rotation on the soil and yield parameters of sorghum. Mean separations were performed using Duncan's Multiple Range Test at a significance level of $p < 0.05$.

3.4. Results

3.4.1. Effects of planting date, tillage, cultivar and rotation on plant height and dry matter

3.4.1.1. Plant height and dry matter at Mphanama in season three

Tillage, cultivar and crop rotation as main factors and their interactions including planting date in season three (only one reported) did not significantly affect plant height (Table 3.2). Plant height ranged from 93.6 – 98.4 cm irrespective of tillage, cultivar and rotation (Table 3.3). However, planting date as a main factor significantly ($p < 0.05$) affected plant height with early planted sorghum resulting in taller plants (101 cm) than late planted crops (91.0 cm) (Table

3.3). All the measured treatments as main factors and their interactions also did not significantly affect sorghum dry matter yield, which ranged from 1.82 – 2.26 t ha⁻¹ (Table 3.2).

Table 3.2: p-values of sorghum growth parameters as affected by planting date, tillage, cultivar, rotation as well as the interactions in season three at Mphanama.

Treatment	df	Plant height	Dry matter	Grain yield	TSW
p-value					
PD	1	0.035*	0.730	0.269	0.010*
Tillage	1	0.306	0.885	0.386	0.399
Cultivar	1	0.416	0.125	0.259	0.058
Rotation	1	0.361	0.595	0.071	0.134
PD * Tillage	1	0.230	0.769	0.007*	0.935
PD * Cultivar	1	0.244	0.729	0.257	0.146
PD * Rotation	1	0.375	0.598	0.186	0.975
Tillage * Cultivar	1	0.389	0.761	0.743	0.281
Tillage * Rotation	1	0.369	0.649	0.890	0.613
Cultivar * Rotation	1	0.342	0.701	0.263	0.436
PD*Tillage*Cultivar	1	0.313	0.852	0.232	0.291
PD*Tillage*Rotation	1	0.361	0.127	0.391	0.328
PD*Cultivar*Rotation	1	0.309	0.233	0.536	0.946
Tillage*Cultivar*Rotation	1	0.379	0.397	0.450	0.579
PD*Tillage*Cultivar*Rotation	1	0.416	0.486	0.372	0.977

Note: df – degree of freedom; PD – planting date.

Table 3.3: Effects of planting date, tillage, cultivar and rotation on sorghum growth parameters in season three (2022 – 2023) at Mphanama.

Treatment	Plant height (cm)	Dry matter (t ha ⁻¹)	Grain yield (t ha ⁻¹)	TSW (g)
Planting date				
Early	101 a	1.99a	1.36a	26.9 a
Late	91.0 b	2.09a	1.11a	22.7 b
p-value	p<0.05	ns	ns	p<0.05
Tillage				
NT	98.4a	2.06a	1.33a	25.5a
CT	93.6a	2.02a	1.13a	24.2a
p-value	ns	ns	ns	ns
Cultivar				
Pan8816	97.9a	2.26a	1.36a	26.3a
Macia	94.1a	1.82a	1.10a	23.3a
p-value	ns	ns	ns	ns
Rotation				
S-C-S	98.1a	1.97a	1.45a	26.0a
S-S-S	93.9a	2.12a	1.02a	23.6a
p-value	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum.

3.4.1.2. Plant height and dry matter at Clau-Clau in seasons two and three

In season two, all treatments and their interactions had no significant effects on plant height except planting date as a main factor and the interaction of planting date × tillage × cultivar in the second growing season (Table 3.4). Early planting generally resulted in taller sorghum plants (133 cm) than late planted sorghum (92.1 cm) during the second growing season (Table 3.5). The magnitude of the difference was significantly influenced by interaction with planting date, tillage and cultivar in the second growing season. For instance, early planting × NT ×

Pan8816 had the highest average height (138 cm), whilst several other combinations with early planting, including both cultivars and tillage practices also had significantly taller plants compared to late planting $\times$ NT $\times$ Macia (56.7 cm) and late planting $\times$ CT $\times$ Pan8816 (62.0 cm) (Figure 3.5). Examples of this include early planting $\times$ NT $\times$ Macia (133 cm), early planting $\times$ CT $\times$ Pan8816 (133 cm) and early planting $\times$ CT $\times$ Macia (126 cm). For early planting, there was no differences in plant height between the two cultivars under either NT or CT. However, under late planting and NT, Pan8816 plants were taller than Macia. Conversely, the opposite was true under CT. Plant height ranged from 108 – 116 cm irrespective of tillage and cultivar in season two (Table 3.5), while it ranged from 103 – 107 cm irrespective of planting date, tillage, cultivar and rotation (Table 3.7). In season 3, planting date, tillage, cultivar, rotation and their interactions had no significant effects on sorghum plant height (Table 3.6).

All the treatments and their interactions did not have significant effects on sorghum dry matter yield in the second (Table 3.4) and third (Table 3.6) growing seasons except planting date as a main factor in the second growing season. Early planting resulted in a significant increase in sorghum dry matter weight compared to late planting in the second growing season. Dry matter weight was nearly double at early planting (2.38 t ha^{-1}) compared to late planting (1.10 t ha^{-1}) in season two (Table 3.5). Dry matter ranged from $1.51 - 1.98 \text{ t/ha}$ irrespective of tillage and cultivar in season two (Table 3.5) while in season three it ranged from $2.12 - 2.69 \text{ t ha}^{-1}$ irrespective of planting date, tillage, cultivar and rotation (Table 3.7).

Table 3.4: p-values of sorghum growth parameters as affected by planting date, tillage, cultivar, rotation as well as the interactions in season two at Clau-Clau.

Treatment	df	Plant height	Dry matter	Grain yield	TSW
p-value					
PD	1	<0.0001*	0.003*	0.022*	0.039*
Tillage	1	0.453	0.232	0.697	0.419
Cultivar	1	0.261	0.198	0.431	0.143
PD * Tillage	1	0.898	0.845	0.731	0.211
PD * Cultivar	1	0.803	0.396	0.547	0.419
Tillage * Cultivar	1	0.489	0.172	0.153	0.419
PD*Tillage*Cultivar	1	<0.0001*	0.744	0.628	0.211

Note: df – degree of freedom; PD – planting date.

Table 3.5: Effects of planting date, tillage and cultivar on sorghum growth parameters in the second growing season (2020/21) at Clau-Clau.

Treatment	Plant height (cm)	Dry matter (t ha ⁻¹)	Grain yield (t ha ⁻¹)	TSW (g)
Planting date				
Early	133a	2.38a	1.33a	48.3a
Late	92.1b	1.10b	0.56b	35.5b
p-value	p<0.05	p<0.05	p<0.05	p<0.05
Tillage				
NT	115a	1.96a	0.88a	43.3a
CT	110a	1.51a	1.00a	37.5a
p-value	ns	ns	ns	ns
Cultivar				
Pan8816	116a	1.98a	1.07a	45.8a
Macia	108a	1.49a	0.82a	35.0a
p-value	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage.

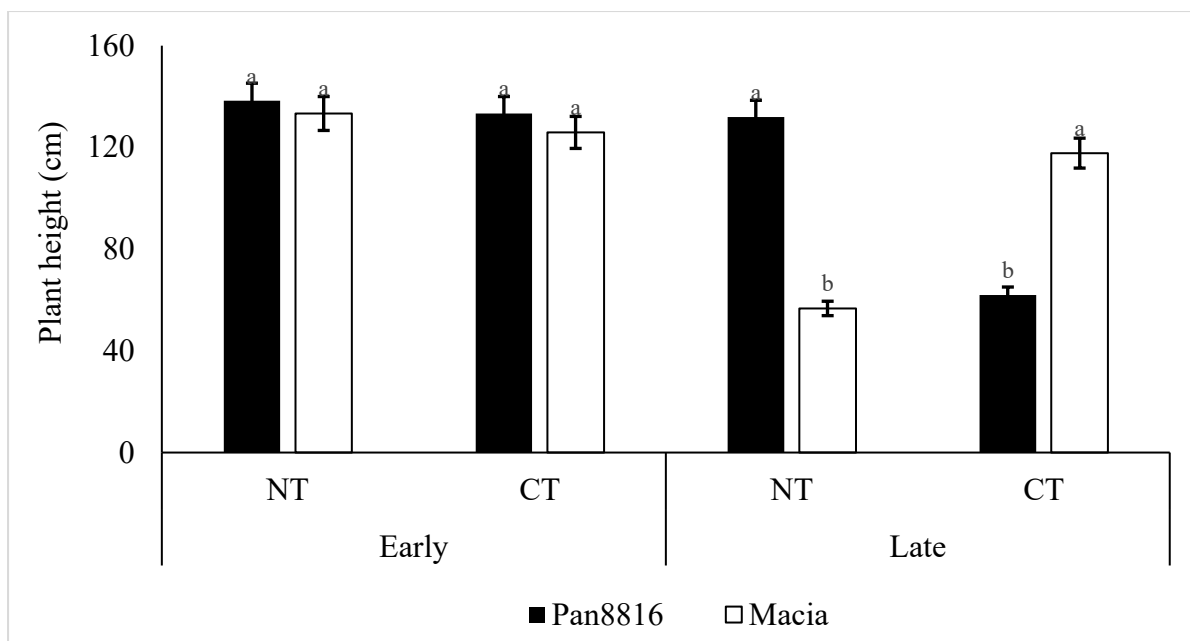


Figure 3.5: Interaction effects of planting date, tillage and cultivar on plant height in the second growing season at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

Table 3.6: p-values of sorghum growth parameters as affected by planting date, tillage, cultivar, rotation as well as the interactions in season three at Clau-Clau

Treatment	df	Plant height	Dry matter	Grain yield	TSW
PD	1	0,492	0.387	0.547	0.034*
Tillage	1	0.158	0.674	0.427	0.009*
Cultivar	1	0.931	0.214	0.912	0.261
Rotation	1	0.297	0.383	0.788	0.129
PD * Tillage	1	0.899	0.655	0.971	0.334
PD * Cultivar	1	0.203	0.850	0.545	0.644
PD * Rotation	1	0.279	0.712	0.677	0.974
Tillage * Cultivar	1	0.321	0.757	0.410	0.508
Tillage * Rotation	1	0.701	0.275	0.144	0.162
Cultivar * Rotation	1	0.140	0.077	0.491	0.070
PD*Tillage*Cultivar	1	0.101	0.966	0.215	0.917
PD*Tillage*Rotation	1	0.345	0.130	0.097	0.991
PD*Cultivar*Rotation	1	0.062	0.864	0.246	0.579
Tillage*Cultivar*Rotation	1	0.351	0.644	0.675	0.166
PD*Tillage*Cultivar*Rotation	1	0.661	0.768	0.429	0.284

Note: df – degree of freedom; PD – planting date.

3.4.2. Effects of planting date, tillage, cultivar and rotation on sorghum grain yield at both sites

All treatments and their interactions had no significant effects on sorghum grain yield except for the interactions of planting date and tillage in season three at Mphanama (Table 3.2). The grain yield ranged from 1.02 – 1.45 t ha⁻¹ irrespective of planting date, tillage, cultivar and rotation in season three at Mphanama (Table 3.3). Under NT treatment, early planted sorghum (1.79 t ha⁻¹) had significantly higher grain yield than late planted sorghum (0.88 t ha⁻¹), and also when compared to early planting under CT plots (0.93 t ha⁻¹) (Figure 3.6). The late planted crop under CT did not differ from any combination with NT and CT with early planting (Figure 3.6). In season two at Clau-Clau, planting date significantly ($p < 0.05$) affected sorghum grain yield with higher grain yield observed at early planting than late planting (1.33 and 0.56 t/ha, respectively) (Table 3.5). Contrary to this, tillage and cultivar as main factors had no significant

effects on sorghum grain yield in season two at Clau-Clau (Table 3.4). All treatments and their interactions also did not significantly affect sorghum grain yield in the third growing season at Clau-Clau (Table 3.6). Grain yield ranged from 0.82 – 1.07 t ha⁻¹ irrespective of tillage and cultivar in season two (Table 3.5) while it ranged from 1.29 – 1.54 t ha⁻¹ irrespective of planting date, tillage, cultivar and rotation in season three at Clau-Clau (Table 3.7).

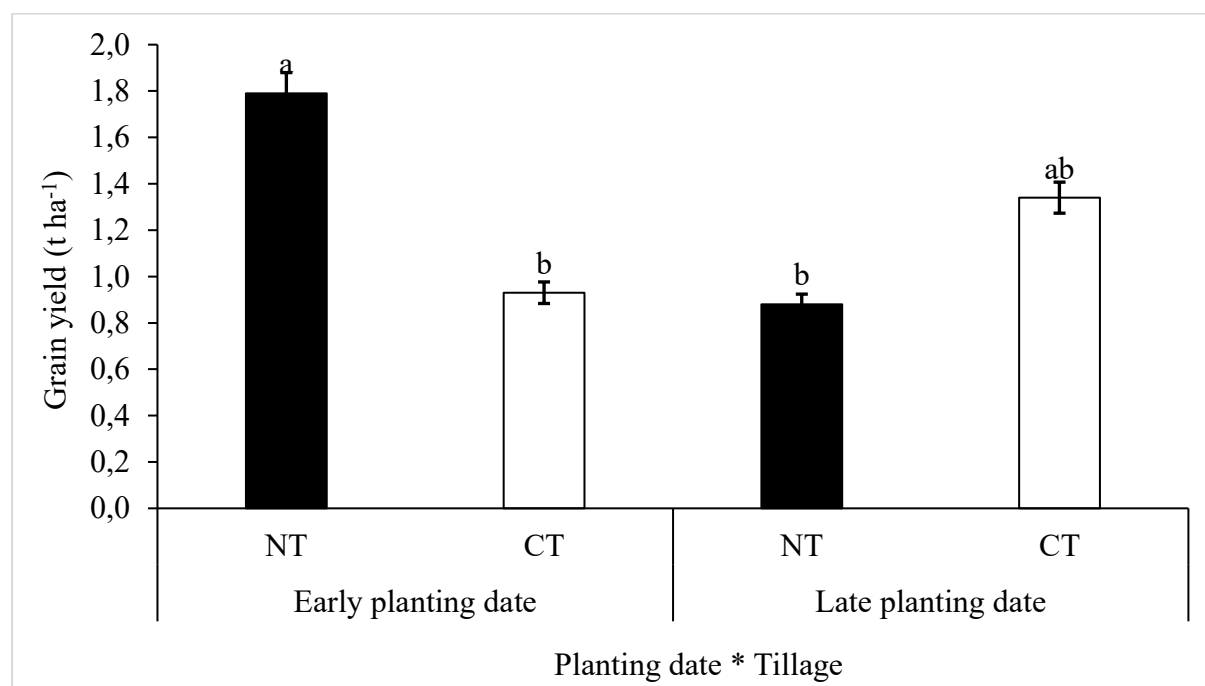


Figure 3.6: Interaction effects of planting date and tillage on sorghum yield in season three at Mphanama village. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

3.4.3. Effects of planting date, tillage, cultivar and rotation on TSW at both sites

At Mphanama, all treatment and their interactions had no significant effects on TSW (Table 3.2), except that early planted sorghum (26.9 g) had significantly ($p < 0.05$) heavier TSW than late planted sorghum (22.7 g) (Table 3.3). A similar trend was observed in season two at Clau-Clau, with early planted sorghum leading to greater TSW than late planted sorghum (Table 3.4). The TSW were significantly ($p < 0.05$) higher by 36.1% when planted early compared to late planting in season two (Table 3.5). In contrast to season two at Clau-Clau, the late planted sorghum had significantly ($p < 0.05$) greater TSW than early planted sorghum (28.7 and 23.2 g,

respectively) in the third growing season at Clau-Clau (Table 3.7). Moreover, significantly ($p<0.05$) greater TSW was also observed when sorghum was planted under NT compared to CT plots in season three (29.4 and 22.4 g, respectively) at Clau-Clau (Table 3.7). However, the other treatments and the combination of all treatments did not significantly affect sorghum weight in the second (Table 3.4) and third (Table 3.6) growing seasons at Clau-Clau. The TSW ranged from 35.0 – 45.8 g irrespective of tillage and cultivar in season two (Table 3.5), while it ranged from 24.0 – 27.9 g irrespective of cultivar and rotation in season three at Clau-Clau (Table 3.7). At Mphanama, the TSW ranged from 23.3 – 26.3 g irrespective of tillage, cultivar and rotation in season three (Table 3.3).

Table 3.7: Effects of planting date, tillage, cultivar and rotation on sorghum growth parameters in the third growing season (2021/22) at Clau-Clau.

Treatment	Plant height (cm)	Dry matter (t ha ⁻¹)	Grain yield (t ha ⁻¹)	TSW (g)
Planting date				
Early	106a	2.60a	1.51a	23.2b
Late	104a	2.21a	1.32a	28.7a
p-value	ns	ns	ns	$p<0.05$
Tillage				
NT	103a	2.31a	1.29a	29.4a
CT	107a	2.50a	1.54a	22.4b
p-value	ns	ns	ns	$p<0.05$
Cultivar				
Pan8816	105a	2.12a	1.39a	27.4a
Macia	105a	2.69a	1.43a	24.5a
p-value	ns	ns	ns	ns
Rotation				
S-C-S	106a	2.21a	1.45a	24.0a
S-S-S	103a	2.60a	1.37a	27.9a
p-value	ns	ns	ns	ns

Note: Different letters (a and b) – significant differences ($p < 0.05$); ns – not significant; NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum.

3.4.4. Effects of planting date, tillage, and rotation on selected soil properties

3.4.4.1. Soil properties at Mphanama

The interaction of planting date, tillage and crop rotation did not significantly affect all the measured soil properties in the second growing season (Table 3.8). Planting date, tillage and rotation did not significantly affect total N, K and pH in season two (Table 3.8; Table 3.9). The concentration of total N ranged from 0.07 – 0.08%, K ranged from 268 – 303 mg kg⁻¹ and pH ranged from 8.29 – 8.41 irrespective of planting date, tillage and rotation in season two (Table 3.9). Crop rotation as a main factor also did not have a significant effect on all the measured soil properties in the second and third growing season (Table 3.8). However, planting date significantly affected exchangeable Ca and Mg. Late planting resulted in 14.3% higher exchangeable Ca and 16.8% higher exchangeable Mg than early planted plots in the second growing season (Table 3.9). Tillage also significantly affected available P and exchangeable Ca in the second growing season while it did not affect all measured soil properties in season three (Table 3.8). No-tillage resulted in 24.5% higher available P compared to CT, while the NT treatment resulted in 10.3% lower exchangeable Ca than the CT treatment in the second growing season (Table 3.9).

The interaction between planting date and tillage significantly affected exchangeable Ca in the second growing season (Table 3.8). Both NT and CT treatments had significantly higher exchangeable Ca when planted late and also CT treatment had a significant higher exchangeable Ca when planted early compared to the NT treatment when planted early (Figure 3.7). In season three, planting date significantly affected exchangeable Ca and Mg, and the interaction of planting date and rotation significantly affected available K, while the other treatments and their interactions did not significantly affect any of the measured soil properties (Table 3.8). Late planting resulted in 18.3% higher exchangeable Ca and 22.0% higher exchangeable Mg compared to early planting (Table 3.10). The rotation of sorghum-cowpea-sorghum had significantly higher available K than the same rotation under early planting in the third growing season (Figure 3.8). The concentration of total N ranged from 0.05 – 0.06 %, P

ranged from 82.5 – 89.8 mg kg⁻¹, K ranged from 317 – 348 mg kg⁻¹ and pH ranged from 8.53 – 8.61, irrespective of planting date, tillage and rotation in season three (Table 3.10).

Table 3.8: p-values of soil properties as affected by planting date, tillage, rotation as well as the interactions in season two and three at Mphanama.

Treatment	df	Total N	P	K	Ca	Mg	pH
p-value							
Season two							
PD	1	0.441	0.257	0.077	0.003*	0.007*	0.060
Tillage	1	0.363	0.010*	0.230	0.012*	0.974	0.790
Rotation	1	0.725	0.118	0.449	0.533	0.646	0.632
PD * Tillage	1	0.187	0.932	0.090	0.047*	0.053	0.915
PD * Rotation	1	0.833	0.380	0.653	0.501	0.710	0.340
Tillage * Rotation	1	0.623	0.615	0.546	0.908	0.810	0.381
PD * Tillage * Rotation	1	0.725	0.892	0.376	0.185	0.306	0.278
Season three							
PD	1	0.054	0.304	0.323	0.030*	0.002*	1.000
Tillage	1	0.217	0.339	0.121	0.091	0.228	0.162
Rotation	1	0.217	0.978	0.890	0.547	0.100	0.107
PD * Tillage	1	0.056	0.987	0.900	0.172	0.240	0.528
PD * Rotation	1	0.217	0.675	0.027*	0.443	0.165	0.241
Tillage * Rotation	1	0.667	0.976	0.095	0.541	0.914	0.064
PD*Tillage*Rotation	1	0.667	0.841	0.182	0.682	0.436	0.076

Note: df – degree of freedom; PD – planting date; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium.

Table 3.9: Effects of planting date, tillage and rotation on selected soil properties in season two (2020-2021) at Mphanama.

Treatment	Total N %	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	pH (H ₂ O)
Planting date						
Early	0.07a	65.4a	268a	3368b	125b	8.41a
Late	0.08a	71.8a	303a	3851a	146a	8.29a
p-value	ns	ns	ns	p<0.05	p<0.05	ns
Tillage						
NT	0.07a	76.1a	297a	3413b	136a	8.35a
CT	0.08a	61.1b	274a	3807a	135a	8.34a
p-value	ns	p<0.05	ns	p<0.05	ns	ns
Rotation						
S-C-S	0.07a	73.0a	293a	3563a	137a	8.35a
S-S-S	0.07a	64.2a	278a	3657a	134a	8.34a
p-value	ns	ns	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium.

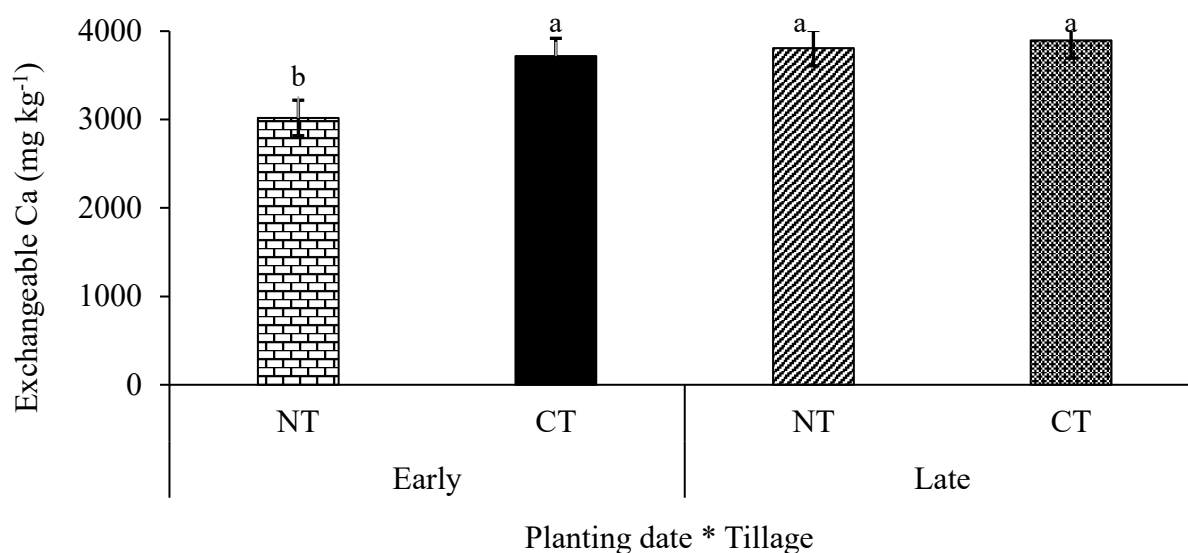


Figure 3.7: Effects of planting date and tillage on Calcium (Ca) in season two at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

Table 3.10: Effects of planting date tillage and rotation on selected soil properties in season three (2022-2023) at Mphanama village.

	Total N	P	K	Ca	Mg	pH
Treatment	%	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(mg kg ⁻¹)	(H ₂ O)
Planting date						
Early	0.05a	82.5a	323a	4053b	132b	8.57a
Late	0.06a	89.8a	342a	4793a	161a	8.57a
p-value	ns	ns	ns	$p < 0.05$	$p < 0.05$	ns
Tillage						
NT	0.05a	89.5a	348a	4151a	142a	8.61a
CT	0.06a	82.8a	317a	4694a	151a	8.54a
p-value	ns	ns	ns	ns	ns	ns
Rotation						
S-C-S	0.06a	86.0a	331a	4511a	153a	8.53a
S-S-S	0.05a	86.2a	334a	4334a	140a	8.61a
p-value	ns	ns	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences ($p < 0.05$); ns – not significant; NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum.

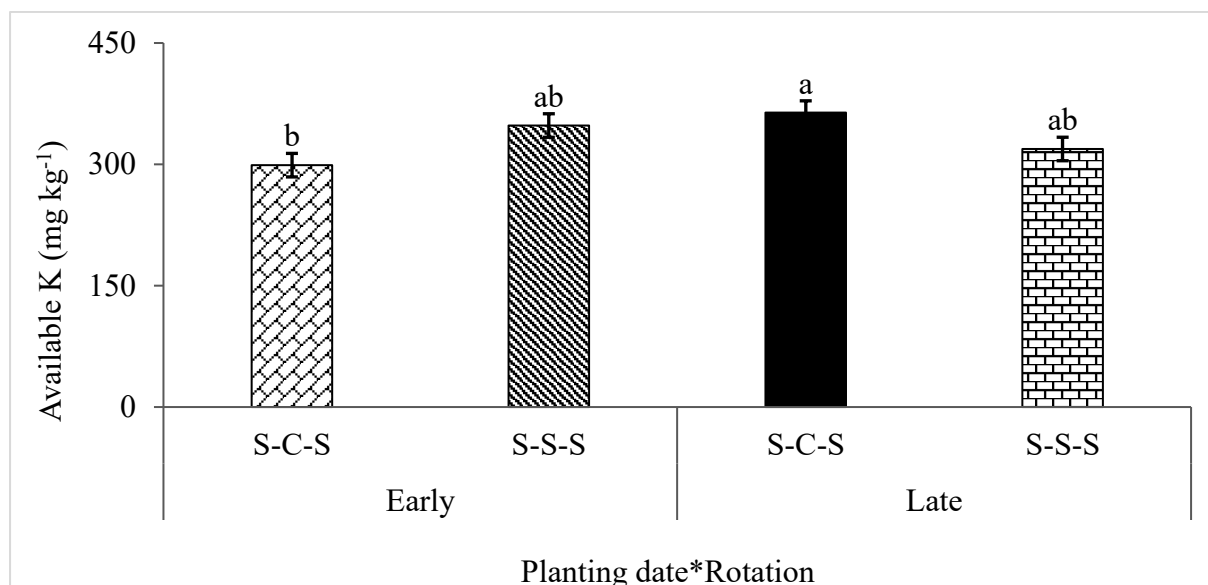


Figure 3.8: The effects of planting date and rotation on available potassium (K) in season three at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

3.4.4.2. Soil properties at Clau-Clau

The interactions between planting date, tillage and rotation had no significant effects on any of the measured soil properties in season two and three at Clau-Clau (Table 3.11). Additionally, planting date and rotation as main factors did not have significant effects on soil properties measured except that planting date significantly affected exchangeable Ca in the second season and affected available K in season three of the study (Table 3.11). Tillage alone also did not significantly affect total N, Ca, Mg and pH in season two. Late planting significantly decreased the exchangeable Ca by 29.3% than early planting in the second growing season and decreased available K by 23.3% in the third season (Table 3.12; Table 3.13). Tillage also significantly affected available P and K in season two and significantly affected only total N in season three of the study (Table 3.11). Furthermore, the rotation of sorghum-cowpea-sorghum (S-C-S), and sorghum-sorghum-sorghum (S-S-S) under NT treatments and the combination of sorghum-sorghum-sorghum (S-S-S) under CT treatments, significantly increased available P than the

interaction of sorghum-cowpea-sorghum (S-C-S) under CT treatment in season two (Figure 3.9). In the third growing season, crop rotation did not significantly affect any of the measured soil properties (Table 3.11). Tillage significantly affected total N with NT plots showing a 50.0% increase in total N compared to CT plots in season three (Table 3.13). Planting date significantly affected exchangeable K with higher K observed under early than late planting (49.3 and 37.8 mg kg⁻¹, respectively) in season three (Table 3.13). The interaction between planting date and rotation significantly affected available K with the rotation of S-S-S under early planting resulting in higher available K than all other combination treatments in season three (Figure 3.10). Moreover, the combination of NT with S-S-S had a significantly higher available K compared to the other combinations in the third growing season (Figure 3.11).

Table 3.11: p-values of soil properties as affected by planting date, tillage, cultivar and rotation, as well as the interactions in season two and three at Clau-Clau.

Treatment	df	Total N	P	K	Ca	Mg	pH
p-value							
Season two							
PD	1	1.000	0.676	0.868	0.049*	0.125	0.055
Tillage	1	0.153	0.028*	0.004*	0.139	0.852	0.068
Rotation	1	0.264	0.181	0.165	0.550	0.876	0.105
PD * Tillage	1	0.423	0.930	0.582	0.680	0.748	0.401
PD * Rotation	1	0.872	0.208	0.330	0.694	0.838	0.646
Tillage * Rotation	1	1.000	0.019*	0.104	0.358	0.699	0.370
PD * Tillage * Rotation	1	0.337	0.857	0.188	0.844	0.781	0.771
Season three							
PD	1	0.217	0.245	0.001*	0.330	0.100	0.447
Tillage	1	0.004*	0.406	0.081	0.715	0.410	0.653
Rotation	1	0.667	0.202	0.062	0.575	0.564	0.371
PD * Tillage	1	0.056	0.389	0.489	0.594	0.659	0.509
PD * Rotation	1	0.056	0.828	0.013*	0.274	0.475	0.266
Tillage * Rotation	1	0.667	0.800	0.030*	0.472	0.303	0.327
PD * Tillage * Rotation	1	0.217	0.435	0.081	0.783	0.379	0.548

Note: df – degree of freedom; PD – planting date.

Table 3.12: Effects of planting date, tillage and rotation on selected soil properties in season two (2020-2021) at Clau-Clau.

Treatment	Total N %	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	pH (H ₂ O)
Planting date						
Early	0.05a	18.9a	40.1a	157a	42.9a	5.20a
Late	0.05a	20.1a	39.7a	111b	33.4a	5.07a
p-value	ns	ns	ns	p<0.05	ns	ns
Tillage						
NT	0.06a	22.8a	43.8a	151a	38.7a	5.26a
CT	0.05a	16.2b	36.0b	117a	37.6a	5.10a
p-value	ns	p<0.05	p<0.05	ns	ns	ns
Rotation						
S-C-S	0.05a	17.5a	41.7a	127a	37.7a	5.11a
S-S-S	0.06a	21.5a	38.1a	141a	38.6a	5.25a
p-value	ns	ns	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium.

Table 3.13: Effects of planting date, tillage and rotation on selected soil properties in season three (2021-2022) at Clau-Clau.

Treatment	Total N %	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	pH (H ₂ O)
Planting date						
Early	0.06a	26.1a	49.3a	148a	38.1a	4.65a
Late	0.05a	31.1a	37.8b	122a	25.8a	4.96a
p-value	ns	ns	p<0.05	ns	ns	ns
Tillage						
NT	0.06a	30.3a	45.7a	139a	29.1a	4.90a
CT	0.04b	26.8a	41.5a	130a	34.8a	4.72a
p-value	p<0.05	ns	ns	ns	ns	ns
Rotation						
S-C-S	0.05a	25.8a	43.6a	127a	30.0a	4.99a
S-S-S	0.06a	31.4a	46.5a	142a	33.9a	4.62a
p-value	ns	ns	ns	ns	ns	ns

Note: Different letters in a column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium.

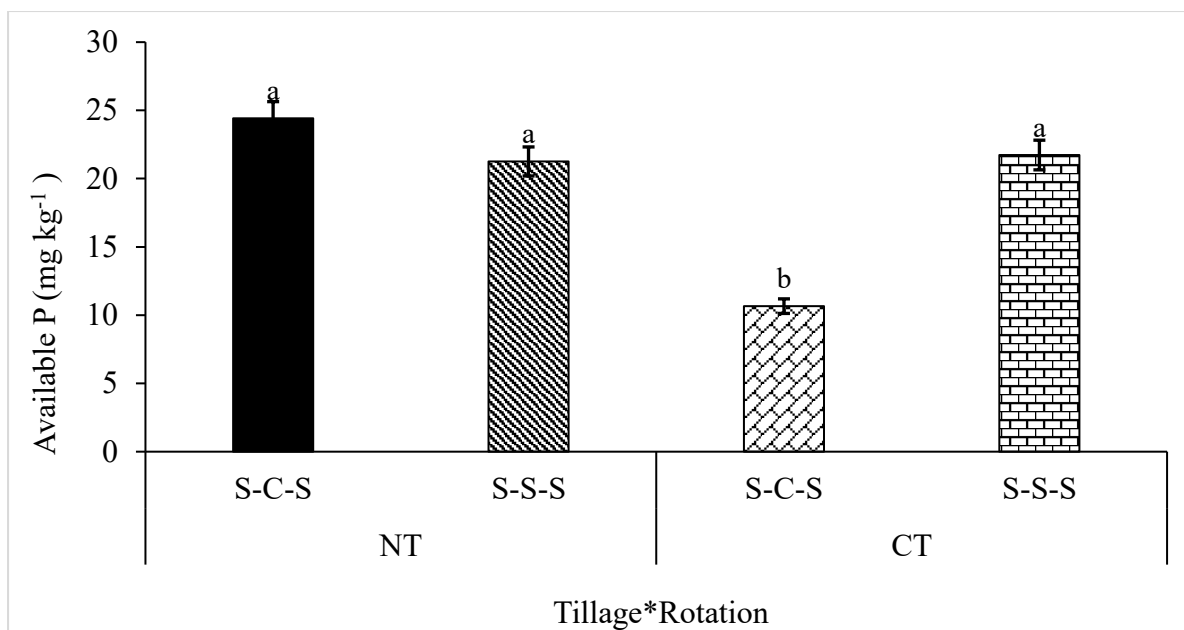


Figure 3.9: Effects of tillage and rotation on available P in season three at Clau-Clau. Different letters (a and b) – significant differences ($p<0.05$); NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

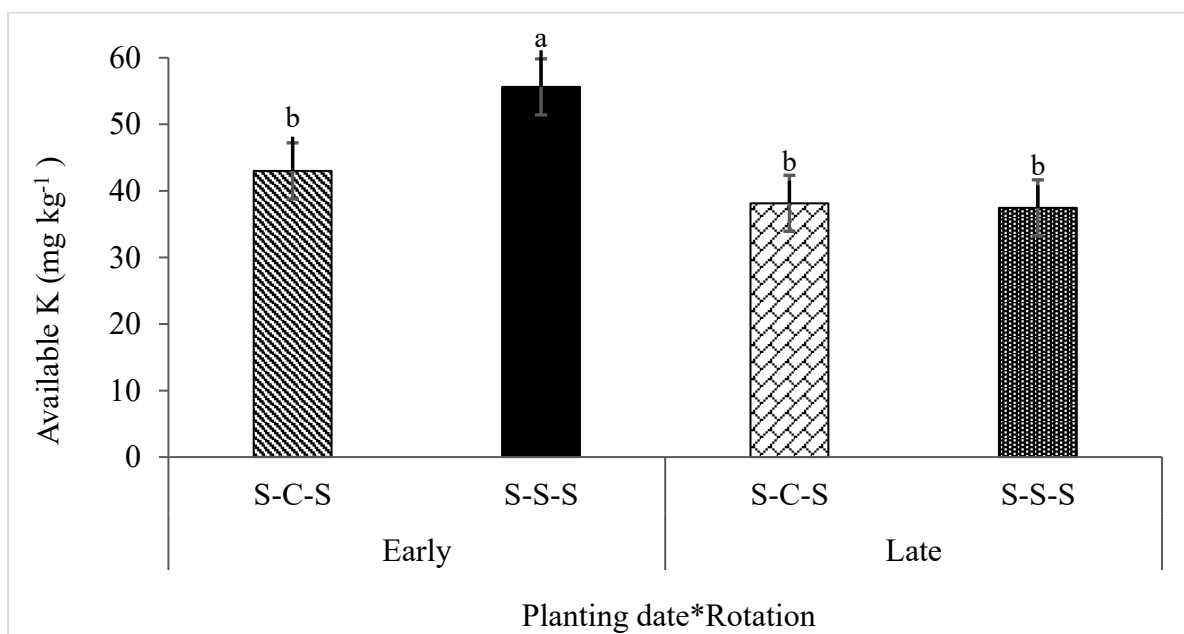


Figure 3.10: Effects of planting date and rotation on available K in season three at Clau-Clau. Different letters (a and b) – significant differences ($p<0.05$); S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

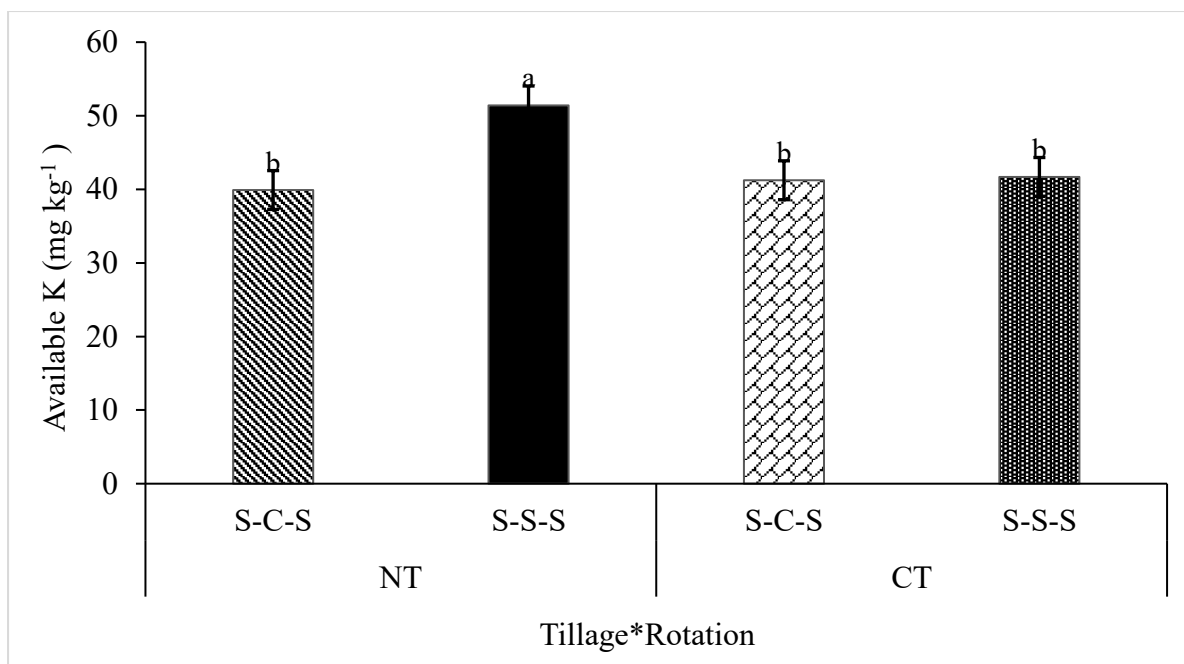


Figure 3.11: Effect of tillage and rotation on available K in season three at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-till; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

3.5. Discussion

Crop growth and development were significantly impacted by the extreme drought and lack of precipitation, which resulted in crop growth and development failure in the second growing season at Mphanama. This result clearly demonstrated that even though sorghum is a drought tolerant crop it can still fail under extreme drought conditions. Extreme drought and lack of precipitation are major limiting factors for crop development and growth across the world (Barnabas et al., 2008; Daryanto et al., 2016; Hadebe et al., 2017a). A previous study conducted by Orimoloye (2022) investigated the response of maize and sorghum production under drought stress (2011 – 2021) in the Free State Province, South Africa. The study found that the production of maize and sorghum were negatively affected by severe drought events in 2015 and 2018. Water stress during vegetative and reproductive stages can possibly reduce yield by more than 36% and 55%, respectively (Assefa et al., 2010). Water stress delays crop root growth and maturity of the crop which likely results in reduced agricultural productivity or crop failure (Ge et al., 2012a; Piscitelli et al., 2021). Extreme drought stress at an early stage of a crop can cause crop leaves to curl and can lead to stunted crop growth (Kim and Lee,

2023). The taller plant height with early planting in the third growing season at Mphanama could be attributed to the early rainfall, which might have positively influenced the crop emergence, germination and the vegetative growth development stages compared to the late planted sorghum plants. The late planted sorghum might also have been affected by the extreme heat waves experienced at the site, which increased water stress during their growth development stages. When plants experience water stress and extreme temperatures they stop growing and quickly transition to flowering and reproductive stages to quickly complete their life cycle (Abaza et al., 2023). Baumhardt et al. (2011) reported that, the lack of rainfall during planting prohibits the establishment of dryland plants, consequently, limiting crop growth. The results are consistent with previous studies that reported taller sorghum plants with early planting while shorter sorghum plants with less time for vegetative growth were observed at late planting (Almodares and Darany, 2006).

At Clau-Clau, the taller sorghum plants observed in the second growing season could be attributed to the observed higher K content at early planting. The taller sorghum plants observed when Pan8816 cultivar was planted under the NT system in the second growing season at Clau-Clau could be attributed to low soil disturbance and the addition of the plant residues, which might have improved P and K. Thus, P and K were higher under NT plots in the second growing season, which might have played an important role to enhance the growth development of the sorghum. A previous study on the response of grain sorghum production found that the application of potassium sulphate significantly increased sorghum grain and its biological yields compared to the control (Asgharipour and Heidari, 2011). The authors concluded that adequate application of K can improve the drought resistance of grain sorghum, which might have been the same reason in this study, hence improved the growth of grain sorghum. Potassium (K) improves stomatal regulation, photosynthesis and protein synthesis, which all play vital roles in improving crop growth (Quintero et al., 1998). Both the application of P and K improved sorghum fodder and dry matter yields in an Aridisols under different climatic conditions (Qamar et al., 2022). The retention of crop residues might also improve soil water availability by reducing evaporation and runoff (Verhulst et al., 2011; Mohammad et al., 2012). Moreover, the results show that Pan8816 performed well under NT whereas Macia performed better under CT in the second season. This difference might be attributed to the cultivar's genotype adaptation under different tillage systems. However, both cultivars performed well under both NT and CT when planted early, thus highlighting the importance of timeous planting. The results of this study suggest that different sites may have similar trend

in results, but are affected by different factors. For instance, the taller sorghum plants observed in the second growing season at Clau-Clau could be attributed to the higher K content with early planting, whilst in Mphanama the early rainfall could be the main factor affecting crop growth. A previous study on the response of maize growth to different planting dates reported that early planting is associated with higher yield (Zhou et al., 2016).

The significantly higher dry matter observed with early planting in the second season at Clau-Clau could be attributed to the taller sorghum plants produced at the early planting date. Plant height has a positive relationship with dry matter yield, indicating that, taller plant accumulates more dry matter (Shukla et al., 2017). Results from a linear model proved that an increase in maize plant height positively increase maize dry matter accumulation at silking and physiological maturity (Liu et al., 2021). The higher yield at early planting in season two at Clau-Clau could be attributed to the observed improved plant growth parameters Early planting resulted in taller sorghum plant, greater dry matter yield and TSW compared to late planting. Plant height, dry matter and TSW were consistent with the results for sorghum yield in season two of this study at Clau-Clau. These results were also in agreement with those reported by Arshad (2021), who found that maize growth parameters including dry matter, had a strong positive correlation ($r = 0.84 - 0.98$) with maize grain yield. Generally, taller plants with a greater dry matter accumulation are better equipped for water extraction, which promotes crop growth development through enhanced photosynthesis, grain filling and hence higher grain yield (Tolk et al., 2013; Hadebe et al., 2017a). The lower grain yield for late planting may also be attributed to the crop physiological stress, which might have been caused by the extreme temperatures towards the end of the crop growth (Wiedenfeld and Matocha, 2010).

At Mphanama, the higher yield observed with early planting under NT plots could be attributed to the significant taller plants and higher TSW observed at early than late planting. Similar results were reported by Zhou et al. (2016), who found that higher maize grain yield was linked to TSW and dry matter yield. Another study on the impacts of climate on summer maize (*Zea mays L*) found a positive linear relationship between maize grain yield and TSW (Ren et al., 2022). Magar et al. (2021) found that maize total grain weight was the most significant maize yield contributing trait with a positive correlation of $r = 0.706$. The increased plant height under NT, although not significantly higher than CT, could also have contributed to the higher yield. Reduced soil disturbance in NT systems can contribute to improved soil water retention and nutrient availability, potentially contributing to enhanced crop growth and yield (Serme et al.,

2015; Ayman, 2023). Furthermore, the combination of early rainfall, residue crop retention and absence of soil disturbance could have improved the soil water availability from the early rainfall and reduced water loss through runoff and evaporation. These findings suggest that planting date can directly affect crop grain yield in Clau-Clau, whereas the interaction of planting date and tillage can be a better treatment in Mphanama to increase crop grain yield.

According to Wang et al. (2012), NT works better in dry seasons than wet seasons, and the results of this study show that Mphanama had received lower rainfall and higher temperature conditions compared to Clau-Clau during the growing seasons. Therefore, early planted sorghum could have received enough rainfall and time for development and growth at Clau-Clau whilst, the combination of NT and early planting date could have increased the crop yield in Mphanama. Greater TSW observed at early planting at Mphanama could be attributed to taller plants at early planting. Similar results were observed in Clau-Clau with greater TSW observed at early planting in the second growing season. These results could be attributed to several factors such as enhanced assimilate accumulation due to improved morphology e.g., taller plants, higher dry matter, and sorghum grain yield. Ren et al. (2022) also reported that, the increase of plant height positively influenced crop morphology, such as ear length and ear rows, which resulted in a significant increase of TSW. Sharma et al. (2016) demonstrated that plant height can be used as a good indicator to measure the vegetative growth and yield of maize crops. Early planting allows for a longer growth duration from the emergence stage to the flowering and panicle initiation, which promotes higher nutrient assimilation (Almodares and Darany, 2006). This could have positively influenced the seed weight. Early planting also ensures improved resource utilisation through the establishment of stronger root systems and better access to soil water and nutrients. According to Hadebe et al (2017b), a higher plant biomass accumulation enhances water extraction for growth and photosynthesis. This improved resource utilization ultimately contributes to larger and heavier seeds during the crucial grain filling stage. The greater TSW under NT plots in the third growing season at Clau-Clau could be attributed to the low soil disturbance and crop residue retention, which might have improved soil water availability in the third growing season. Similar results were previously reported with NT resulting in a significant higher TSW than CT systems in a cereal crop production system (De Vita et al., 2007; Wang et al., 2022). Crop residue retention moderates soil temperature and improves water availability by decreasing soil water loss through evaporation and runoff, consequently, enhanced seed weight during grain filling stage. Soil water is one of the vital factors to influence crop growth and yield (Zhao et al., 2023).

Similarly, higher TSW was reported under NT compared to CT treatment which was attributed to the improvement of soil water under NT by reducing water evaporation (Baumhardt et al 2011). Therefore, the greater TSW observed at early planting at Mphanama and in the second growing season at Clau-Clau highlights the benefits of maximizing the sorghum's growth period and optimizing resource utilization for improved seed development.

The higher Ca and Mg at late planting in season two and three and available K under late planting and S-C-S interactions in season three at Mphanama could be attributed to the lower plant height, grain yield and TSW under late planting compared to early planting suggesting that late planting might had lower nutrient uptake than early planting. Moreover, the results can also be attributed to low rainfall experienced at the site, consequently, prevented leaching of nutrients. Too much rainfall washes away nutrients in the soil particularly in sandy soils because of poor water holding capacity (Huang and Hartemink, 2020; Nwite, 2022). While the higher P observed under NT treatment in season two at Mphanama and the significantly higher P and K levels under NT in season two at Clau-Clau could be attributed to crop residue retention. Crop residue retention improves the availability of P by reducing its adsorption onto mineral surfaces (Mtyobile et al., 2019). Consistent with these findings, previous studies have also reported improvements in P and K under NT with crop residue retention (Yang et al., 2017; Gura and Mnkeni, 2019; Malobane et al., 2020). The NT minimizes soil disturbance, preserving soil structure and promoting the activity of beneficial soil microbial communities that contribute to nutrient cycling and availability.

Surprisingly, the lack of soil disturbance and crop residues retention could not relate with the improvement of Ca in the second growing season at Mphanama. However, the lower exchangeable Ca under the combination of early planting and NT in season two could be influenced by the transition of CT to NT practice and NT might have possible promoted runoff which likely carried away nutrients. The increase in total N under NT in the third growing season at Clau-Clau could be linked to the increased SOC due to additions of crop residues under NT, resulting in increased activities of soil microbes, which are responsible for N fixation (Yang et al., 2017; Li et al., 2018b; Malobane et al., 2020). The results of this study are consisted with the previous study by Malobane et al. (2020) who reported that total N was 15.9% higher under NT than CT plots in sandy clay loam soils under sweet sorghum production system. The higher available P under the combination of NT with both rotations and CT with S-S-S than CT with S-C-S in the second growing season at Clau-Clau could be attributed to

the addition of sorghum crop residues after the first growing season. Thus, sorghum crop residues could have improved the available P during decomposition processes. For instance, N, P and K were improved after crop residues application in a sandy loam soil in a sorghum-wheat rotation system (Soni et al., 2021). Malobane et al. (2020) and Mloza-Banda et al. (2014) also found that the maintenance of crop residues coupled with NT positively enhances soil nutrient levels, including available P of sandy clay loam soils over the short-term. In the second growing season, cowpea could not make it to the maturity stage which might have also played a huge role in lowering the available P than other combinations. The higher available K when S-S-S interacted with early planting could be influenced by the lower rainfall and the successful production of sorghum biomass, compared to suffered cowpea biomass production due to warm temperatures. Similar findings were reported by Bado et al. (2012), who found that sorghum monoculture significantly improved soil nutrient levels including total N, extractable P and available K compared to cotton-groundnut-sorghum rotation after 8 years of cultivation in a sandy soil of very low clay and organic C contents. The non-significant effects of rotation as the main factor on the measured soil properties in both study sites suggest that other factors may have played a larger role. Moreover, the short duration of the study may have limited the potential of the treatments to have any meaningful impact. Additionally, poor crop residue retention due to extreme temperature and limited vegetative growth, particularly under crop rotation with cowpea likely masked the potential benefits of residue retention. When plants are experiencing water stress and extreme temperatures, they stop growing and quickly start flowering hence switching to the reproductive stage to quickly complete their life cycle (Abaza et al., 2023). This poor biomass production may also have masked any potential effects of tillage and rotation on nutrient cycling and soil health.

3.6. Conclusion

This study provides insights into the short-term effects of CA on sorghum production in sandy soils. The results demonstrated that CA alone does not consistently improve crop yield under sorghum production on a sandy soil over the short-term (3 years). The findings also highlight that the combination of CA with optimal planting date significantly improve crop yields and soil properties in both study sites, with better results being realised during seasons with higher rainfall. In both sites, planting date alone showed significant effects on crop growth and yield, with early planting being the more favourable planting time for optimal sorghum production. Cultivar-specific responses of sorghum to planting date and tillage, were demonstrated, with

better performance for Pan8816 under NT and Macia under CT, when planted late at Clau-Clau. Sorghum-based CA systems can significantly improve total N, available P and K in some sandy soils over the short-term (3 years). The interaction of planting date and tillage, planting date and rotation, and the combination of tillage and rotation can improve soil properties in sandy soils over the short-term. Therefore, this finding provides a new perspective on maximising the benefits of CA on yield in similar environments. These observations provide valuable, site-specific guidance for farmers in the Mphanama and Clau-Clau regions and similar environments. The lack of short-term rotation effects observed in this study suggests that for sandy soil, short-term external applications of organic fertilizers, such as manure, may be more beneficial than crop rotation with cowpea. Other drought resistant legumes such as pigeon pea need to be tested as rotation crops in these sorghum-based CA systems. The varied effects of planting date and tillage across seasons highlights the need for site-specific management strategies. Whilst this study provides critical short-term insights, long-term studies are necessary to fully understand the effects of tillage and rotation on soil properties and sorghum yield, in order to enable the development of optimised site-specific agronomic practices, ultimately enhancing agricultural planning and decision making in similar environments.

CHAPTER FOUR

4.0. BENEFITS OF GRAIN SORGHUM-BASED CONSERVATION AGRICULTURE AND PLANTING DATE ON SOIL WATER CONTENT, ORGANIC CARBON FRACTIONS AND SOIL PROTEIN IN SANDY SOILS UNDER RAINFED CONDITIONS

4.1. Abstract

Soil degradation and insufficient soil water threaten the sustainability of crop production under rainfed conditions particularly, in sandy soils. No-tillage (NT), crop residue cover, and crop rotation improve soil water content and soil quality. This study evaluated the effects of tillage, planting date and rotation on soil water content, and soil organic carbon (SOC) fractions, including soil protein in sandy soils under a rainfed grain sorghum production system, in semi-arid and sub-humid conditions. The study was conducted from 2020/21 to 2022/23 at Mphanama village (Limpopo Province) and from 2019/20 to 2021/22 at Clau-Clau village (Mpumalanga Province), South Africa. Both study sites had sandy soils (<10% clay) and low SOC (<1.0% SOC). The experiment was carried out in a randomized complete block design (RCBD) with a strip-split-split-plot treatment structure, replicated three times. Treatments included tillage (conventional tillage (CT) and no-till (NT)), planting date (early and late), crop rotation (with cowpea or continuous sorghum) and cultivar (Pan8816 and Macia). Late planting resulted in over 5.77% higher soil water content in dry months of 2022/23 than early planting, while NT resulted in more than 10.5% higher soil water content than CT also during dry months in 2022 at Mphanama. NT with continuous sorghum had over 7% higher soil water content than other treatments, while NT with S-C-S rotation had 8.38% higher soil water content than CT with continuous sorghum, in dry month in 2022 at Mphanama. In dry months in 2022, the interaction of NT with continuous sorghum and NT with S-C-S had over 8.09% more soil water content, respectively compared to the same rotations under CT at Mphanama. At Clau-Clau, (sub-humid) NT had greater than 9.43% significantly lower soil water content than CT in during dry months in 2021/22, while in wet month, NT resulted in 40.6% lower soil water content compared to CT. Late planting resulted in 17.5% higher SOC in the third season at Mphanama, while NT improved SOC by 34.8% at Clau-Clau, with substantial increases in

mineral associated organic carbon (MAOC) (53.9%), fine particulate organic carbon (POC) (117%), and coarse particulate organic carbon (POC) (100%) compared to CT in the third season. The soil protein significantly increased by 92.1% between season one and three at Mphanama. With early planting, soil protein was higher under NT and lower under CT compared to late planting. The results of this research suggest that the impacts of tillage, planting time and crop rotation on soil water content and SOC fractions in a sandy soil are site specific. In this semi-arid area, soil water content was improved when tillage interacted with crop rotation, while under sub-humid conditions, tillage (CT) alone was the dominant factor. SOC content was increased by late planting date in semi-arid conditions, and by NT and rotation in sub-humid conditions under rainfed sorghum production.

Keywords: Planting date, rotation, SOC fractions, soil water content, tillage.

4.2. Introduction

South African smallholder farmers face several crop production challenges, including insufficient soil water and soil structural degradation particularly on sandy soils (Bonetti et al., 2022). These challenges are influenced by soil management practices including tillage, vegetation type and lack of soil cover. Continuous ploughing disrupts soil structural stability and SOC turnover resulting in promoting surface runoff and erosion (Prescott et al., 2019). Generally, sandy soils have lower water holding capacity than loamy and silty loam soils (Jasper et al., 2006), while sandy loam soils hold less water than clayey loam soils. These effects of texture are worsened by climate change, and the associated severe drought, which causes excessive soil water loss, with greater effects on sandy soils (Lal, 2015). This reduction in soil water content causes water stress, affecting crop physiological and metabolic processes, leading to a decline in agricultural productivity (Yang et al., 2006; Berg and Sheffield, 2018).

Recent severe drought (2016 – 2018) in South Africa (Botai et al., 2017), negatively affected agriculture (Adisa et al., 2019), with maize production declining by 35% across the provinces of Kwazulu-Natal, Free State, Mpumalanga and North West (Adisa et al., 2019). Rainfall in semi-arid regions of South Africa is spatially and temporally variable, often occurring either prematurely or delayed, typically occurring as intense storms (Mupangwa et al., 2007). According to the Intergovernmental Panel on Climate Change (IPCC) report, current global

trends reveal that the frequency and severity of droughts are likely to increase in the future, posing further risks to rainfed agricultural systems (IPCC, 2023). The occurrence of extreme storms combined with intensive tillage and crop residue removal, accelerates soil physical degradation, leading to break down of soil aggregates, collapse of pore networks and depleting soil binding agents including SOC (Oliveira et al., 2019). The SOC is essential in maintaining soil physical structure, chemical composition and biological productivity ultimately enhancing soil fertility as well as water holding capacity (Mikha et al., 2015; Sadeghpour et al., 2017). Binding of soil aggregates with SOM improves aggregation and protects the SOC against rapid decomposition by soil microorganisms (Pulleman and Marinissen, 2004; Bhattacharyya et al., 2009), which together regulate nutrient cycling and retention processes. The disruption of the soil physical structure exposes stored and protected SOC within soil aggregates, making the SOC vulnerable to decomposition, which causes erosion, especially on sandy soils (Blanco-Canqui and Ruis. 2018).

Generally, SOC is extremely low (<1%) in sandy soils, particularly in warm dryland cropping systems, with low rainfall conditions, which results in slower SOC accumulation than in cooler areas (De Varennes and Torres, 2011). Changes in management that will result in the accumulation of SOC are required and, due to their sensitivity, labile SOC fractions, including microbial biomass carbon (MBC) may show early responses (Poeplau and Don, 2013; Singh et al., 2016). Soil protein is one of the important soil properties produced by arbuscular mycorrhizal fungi (AMF), which constitutes 5 – 13 % of total SOC (Singh et al., 2016), is vital in cementing soil aggregates and C sequestration (Wu et al., 2012). According to Son et al. (2024), soil protein improves soil quality by absorbing several cations as well as sequestering some of the heavy metals in the soil. Moreover, the soil protein contains several elements including C (35-40%) and N (2-4%), it also contains different types of C compounds and protein-like substances (Agnihotri et al., 2022). Thus, an increase of SOC and soil protein in sandy soils will likely improve soil structure, water infiltration rate and reduce erosion and runoff, leading to increased soil water availability for crop growth and development in dryland smallholder agriculture. The conservation of soil water is important for crop growth in rainfed agricultural practices (Pathak et al., 2011), particularly in arid (201 – 400 mm) and semi-arid areas (401 – 600 mm) (Nciizah and Wakindiki 2015). High temperatures in these areas increase water loss, therefore, soil water conservation systems that will minimize water loss through runoff and evaporation in sandy soils (< 1% OC and 10% clay content) are required. The

improvement of SOC and water content should therefore be prioritized in dryland cropping systems particularly in sandy soils.

Conservation agriculture (CA), based on minimal tillage, soil cover and crop rotations (Malobane et al., 2018), is considered as an environmentally friendly agricultural system that can enhance soil water conservation and enhance soil aggregate stability (Murungu et al., 2011; Lal, 2015; Das et al., 2018; Oliveira et al., 2019). However, the effectiveness of CA in enhancing soil physical quality depends on the interplay between site specific conditions including climate, soil conditions and characteristics, types of cover crops, and management practices (Hubbard et al., 2013; Derpsch et al., 2014). Contrasting results on the impact of CA on key parameters such as soil water content have been reported particularly on sandy soils (Acharya et al., 2019; Yang et al., 2018). The benefits of CA on SOC are evident, with some studies showing a 20.7% increase in SOC at 0 – 5 cm soil depth under zero tillage than to tilled systems on a sandy loam soil (Zhang et al., 2017). Yang et al. (2018) reported greater soil water content under NT than tilled land system over the short-term (3 years). However, Acharya et al. (2019) found 7.9 and 4.3% greater soil water content within 0 – 15 and 15 – 30 cm soil depths, respectively, under CT than NT systems, on a sandy loam soil. These discrepancies call attention to conduct more research on the effectiveness of CA on sandy soils under semi-arid areas, particularly for smallholder farmers who are vulnerable to various production challenges worsened by climate change.

Smallholder farmers in southern Africa heavily rely on maize production for both food security and income generation (Mupangwa et al., 2018; FAOSTAT, 2019; Dunjana et al., 2022). However, climate change projections indicate a continuous decline in maize yields (Choruma et al., 2022; Matimolane et al., 2022), with the crop being particularly sensitive to harsh climatic conditions including extreme heat waves and soil water deficits, resulting in poor growth at various stages (Cakir, 2004). The subsequent reduction in maize biomass production poses challenges not only to food security but for the full implementation of CA as well, as it may lead to insufficient crop residue retention. This shortage may limit the effectiveness of mulch cover in enhancing soil water retention, and nutrient cycling through decomposition in sandy soils. Sorghum could be a viable alternative to maize due to its tolerance to extreme climatic conditions (Hadebe et al., 2017b). Diversifying cropping systems with climate-resilient crops such as sorghum is crucial for food security and soil health (Dunjana et al., 2022). However, successful production of grain sorghum depends on strong mutualistic

relationships with beneficial soil microorganisms including AMF and other tillage practices such as crop rotation. A strong symbiotic relationship with AMF may enhance nutrition quality in grain sorghum because AMF is considered nutritional symbiosis and major providers of phosphorus to crops (Cobb et al., 2016). Moreover, AMF acts as an extended root system to help sorghum extract water and nutrients in the subsoil as well as improve drought and stress tolerance (Cobb et al., 2016). The introduction of crop rotation with legumes could boost soil fertility and increase biomass production in sorghum-based CA systems, thereby enabling the retention of the requisite amount of mulch to sustain soil productivity. However, the current unpredictable rainfall and temperature patterns complicate planting date decisions for farmers (Hadebe et al., 2017b).

There is lack of comprehensive data on combined impacts of time of planting, tillage practices and crop rotation on soil water content and SOC fractions of sandy soils under sorghum production in the semi-arid and sub-humid areas of South Africa. This research gap highlights the need for further investigation to optimize agricultural practices in these areas. In this study we evaluated the effects of time of planting, tillage, crop rotation and sorghum cultivars on soil water content, soil aggregate stability, and the fractions of SOC in a sorghum-based CA system on sandy soils under a rainfed production system in semi-arid and sub-humid regions. The study was conducted across two different climatic conditions to provide a comprehensive understanding of the effects of these factors on grain sorghum production on sandy soils. The results of this study will contribute valuable scientific knowledge to identify the most suitable combination of management practices for soil health under grain sorghum production on sandy soils. Furthermore, the study aims to provide smallholder farmers with reliable scientific evidence for improving soil health in areas dominated by sandy soils.

4.3. Materials and methods

4.3.1. Site description, experimental design and management

The details of the sites, experimental design, treatments and the management of non-experimental variables are described in Chapter three (Section 3.3.1 – 3.3.3). Soil sampling and method for analysis of the initial soil properties are described in Chapter three, Section 3.3.4. Soil initial properties are presented in Chapter three (Table 3.1).

4.3.2. Soil water content measurements

Soil water content was measured monthly using HydroSense II (HS2; Campbell Scientific, USA) probes (30 cm long) from November 2021 to October 2022 for Clau-Clau village and from November 2022 to October 2023 at Mphanama village. The probes were inserted vertically into the soil up to a depth of 30 cm (Kim et al., 2020). The soil water content value displayed on the HydroSense II (HS2) data logger screen was recorded manually. The soil water measurement was repeated three times on each experimental plot and the process was done randomly.

4.3.3. Soil organic carbon (SOC) determination

The SOC was determined following the Walkley-Black method (Combs and Nathan 1998). Three soil subsamples were collected randomly using a soil auger at 0 – 30 cm depth in each experimental plot. A 1.0 g of air-dried and sieved through 2 mm sieve soil sample was transferred into a plastic bottle, then 10 ml $K_2Cr_2O_7$ and 20 ml of H_2SO_4 were added into the bottle and well mixed. The suspension was diluted with 200 ml of water after 30 minutes of reaction. Then, Fe^{3+} was complexed by adding 10 ml of H_3PO_4 and 0.2 g NaF to the suspension. Ferroin indicator of 2.0 ml was added into the solution, titrated with a ferrous ammonium sulphate solution of 0.5 N until the yellowish green colour changed to a brownish red colour at the endpoint. The concentration of oxidizable SOC was calculated as the difference between the volume of the titrant blank and sample. The SOC was calculated using the following equation 1.

$$SOC = N \times (B - S) \times 0.003 \times \frac{100}{Wt\ of\ soil} \dots\dots\dots 1$$

where, N – FAS standard; B and S – amount of FAS used during titration for the blank and soil sample, respectively (Tola et al., 2018).

4.3.4. Soil particulate organic carbon (POC) size fractions determination

The determination of soil POC fractions were done following the method described by Sainepo et al. (2018). A 20 g of air-dried soil sample (<2 mm) was transferred into a 250 ml plastic bottle, followed by addition of 70 ml of sodium hexa-metaphosphate ($(NaPO_3)_6$) dispersion solution and mixed. The suspension was shaken for 15 hours at the speed of 120 rpm using a

reciprocal shaker. The soils were fractionated by passing through a series of 0.250 mm and 0.053 mm. Materials that passed through 0.053 mm sieve were collected, transferred into a 250 ml bottle, swirled to mix thoroughly and then, 100 ml was sampled. All the collected fractions were dried in the oven at 50°C for 48 hours, and ground using a mortar and pestle to pass through a 0.149 mm sieve. The SOC in each fraction was determined by following Walkley black method. The SOC in the fraction < 0.053 mm was referred to as mineral-associated organic carbon fractions (MAOC), 0.053 – 0.250 mm as fine POC fractions and greater than 0.250 mm as coarse POC fractions (Bhattacharyya et al., 2009; Ramesh et al., 2019).

4.3.5. Soil proteins determination

The autoclaving procedure was followed for the extraction of easily extracted Glomalin (EEG) outlined by Wright et al. (2000). A 1 g of air-dried soil samples was placed into a 50 ml centrifuge tube with 8 ml of 20 mM sodium citrate buffered at pH 8. Samples were then autoclaved at 121°C to remove EEG and centrifuged at 5000 g for 20 minutes and the supernatant was stored at 4°C until purified before analysis. The EEG was purified by precipitating with trichloroacetic acid (TCA) and dialysing against 10 mM borate at pH 8.0 after the precipitation process. The soil protein in the extract was determined using the Bradford protein assay protocol (Bradford, 1976). The standard assay procedure entails the preparation of Bovine Serum Albumin (BSA) standards to a range of 5 – 100 µg protein and dilution of the test sample to the same range per 30 µl sample. A 30 µl of each sample standards were transferred into test tubes and 1.5 ml of the Bradford reagent was added into the tube, then samples were incubated for 5 – 60 minutes at room temperature. The absorbance was measured by spectrophotometer at 595 nm.

4.3.6. Statistical Analysis

The JMP 17 PRO statistical software (SAS, 2021) was used to perform analysis of variance (ANOVA), on the effects of planting date, tillage and rotation on soil water content and SOC fractions. Mean separations were calculated using Duncan's Multiple Range Test at $P < 0.05$. Cultivar differences did not significantly affect any of the other measured soil parameters (Chapter 3: Mabasa et al., 2025) and therefore the results of the effects of cultivar were not included in this paper.

4.4. Results

4.4.1. Effects of planting date, tillage and rotation on soil water dynamics over time

Effects of planting date, tillage and rotation on soil water content at Mphanama

Planting date, tillage and the combination of tillage and rotation significantly increased soil water in season three at Mphanama (Table 4.1). The combination of planting date and tillage significantly increased soil water content only in dry month in 2023, while the combination of planting date and rotation significantly improved soil water content only during wet month in season three at Mphanama. Crop rotation as a main factor and the three ways interaction of planting date, tillage and rotation did not significantly affect soil water content at Mphanama (Table 4.1). Late planting resulted in more than 5.77% higher soil water content than early planting during dry months (2022/23) (Figure 4.1). The NT treatment had greater than 10.5% significantly higher soil water content than CT during dry months (2022/23) at Mphanama (Figure 4.2). The combination of planting date and tillage significantly increased soil water content (Table 4.1), with late planting $\times$ NT significantly increasing soil water content compared to early planting $\times$ NT (9.66% and 9.23%, respectively) during dry month in 2023 at Mphanama (Figure 4.3A). The combination of late planting and S-S-S rotation (10.52%) significantly improved soil water content compared to late planting $\times$ S-C-S (10.12%) and early planting $\times$ S-S-S (10.07%) during wet months in 2023 at Mphanama (Figure 4.3B). Significant interaction effects were also observed between tillage and crop rotation on soil water content during dry months in 2022 at Mphanama (Table 4.1). Under NT $\times$ S-S-S, soil water content was significantly higher compared to NT $\times$ S-C-S, CT $\times$ S-C-S and CT $\times$ S-S-S (41.8, 38.7, 37.1 and 35.7%, respectively) in 2022 (Figure 4.4). When NT interacted with S-C-S rotation, soil water content was improved by 8.38% than under CT $\times$ S-S-S during dry month in 2022 (Figure 4.4). The NT $\times$ S-S-S also had >12.3% higher soil water content than both rotations under CT during dry month in 2022. Under NT $\times$ S-C-S, soil water content was significantly improved compared to CT $\times$ S-C-S and CT $\times$ S-S-S (43.2, 39.9 and 37.4%, respectively) in dry month in 2022 (Figure 4.4).

Table 4.1: p-value of planting date, tillage and rotation, as well as interactions on soil water content at Mphanama in season three.

Treatment	df	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23
p-value of soil water content													
PD	1	0.3919	0.0066*	0.0549	0.0319*	0.1156	0.4272	0.3372	0.1498	0.1411	0.5010	0.5460	0.5466
Tillage	1	0.0003*	0.0004*	0.2287	0.0955	0.6277	0.9599	0.8688	0.1837	0.4997	0.8765	0.2197	0.4832
Rotation	1	0.4236	0.7770	0.9126	0.6151	0.9833	0.0985	0.1097	0.3029	0.4230	0.3572	0.3256	0.9401
PD*Tillage	1	0.5290	0.3950	0.5720	0.6417	0.0954	0.0249*	0.2739	0.1130	0.4353	0.4019	0.5914	0.2712
PD*Rotation	1	0.8757	0.7525	0.4632	0.3057	0.1084	0.6508	0.4994	0.0442*	0.0680	0.0683	0.4340	0.7446
Tillage*Rotation	1	0.0314*	0.0039*	0.8726	0.8986	0.8422	0.0643	0.3682	0.2057	0.7838	0.5690	0.2549	0.1517
PD*Tillage*Rotation	1	0.8274	0.4119	0.2848	0.8838	0.9249	0.6364	0.2193	0.6495	0.6126	0.2598	0.2114	0.9800

Note: df – degree of freedom; PD – planting date.

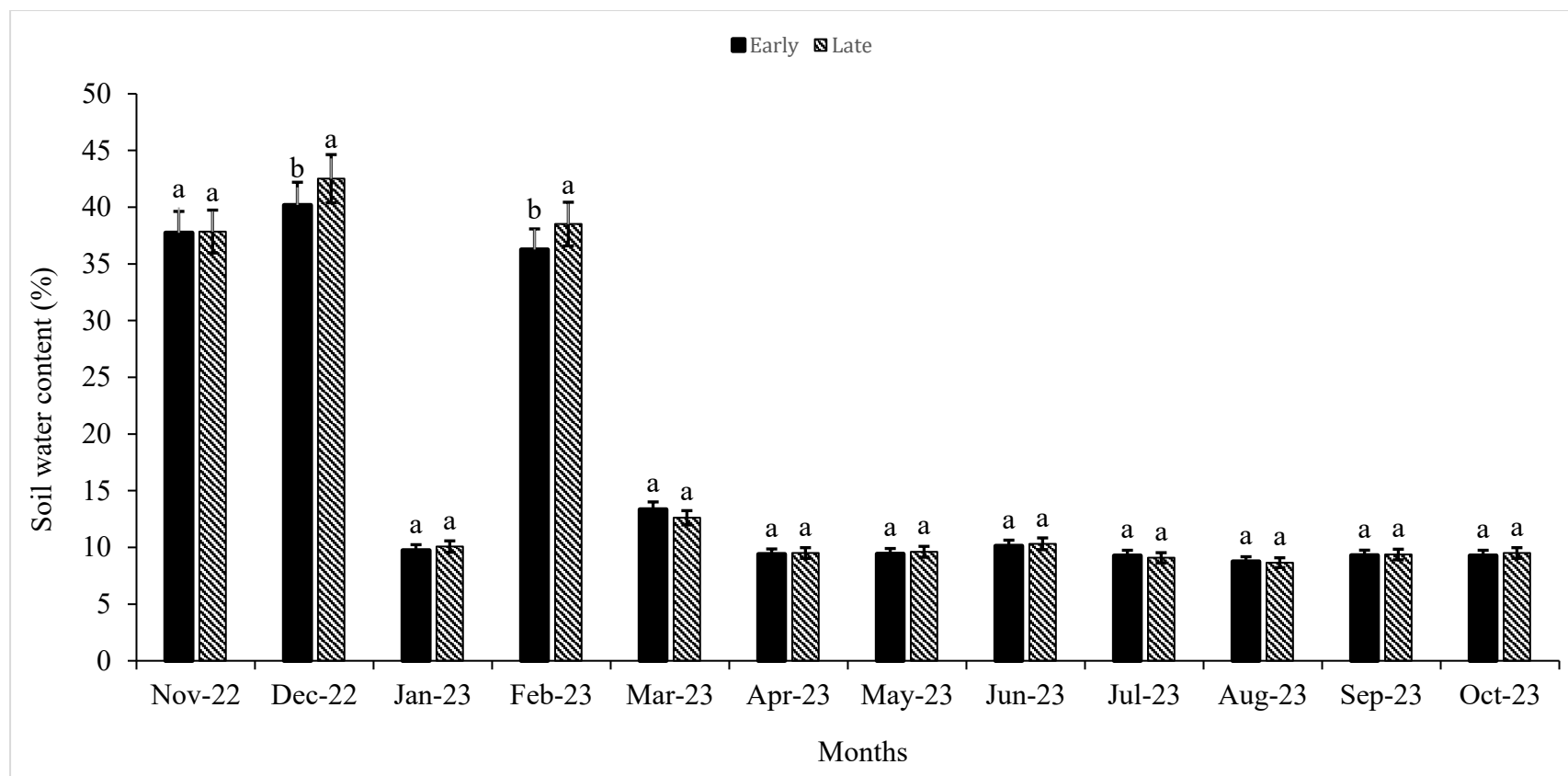


Figure 4.1: Mean monthly soil water content as affected by planting date in season three at Mphanama. Different letters (a and b) – significant differences ($p<0.05$). Bars represent standard error.

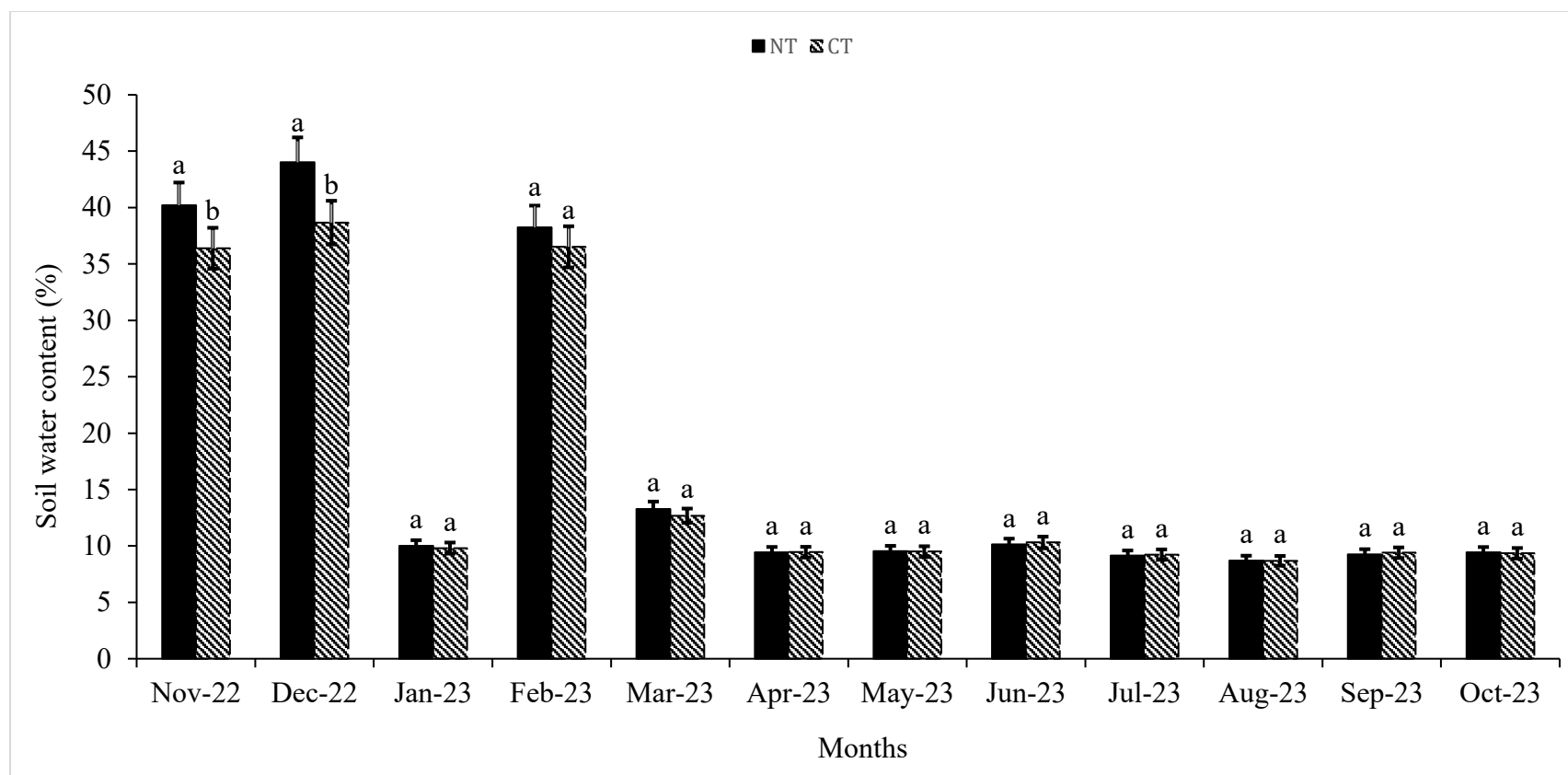


Figure 4.2: Mean monthly soil water content as affected by tillage in season three at Mphanama. Different letters (a and b) – significant differences ($p<0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

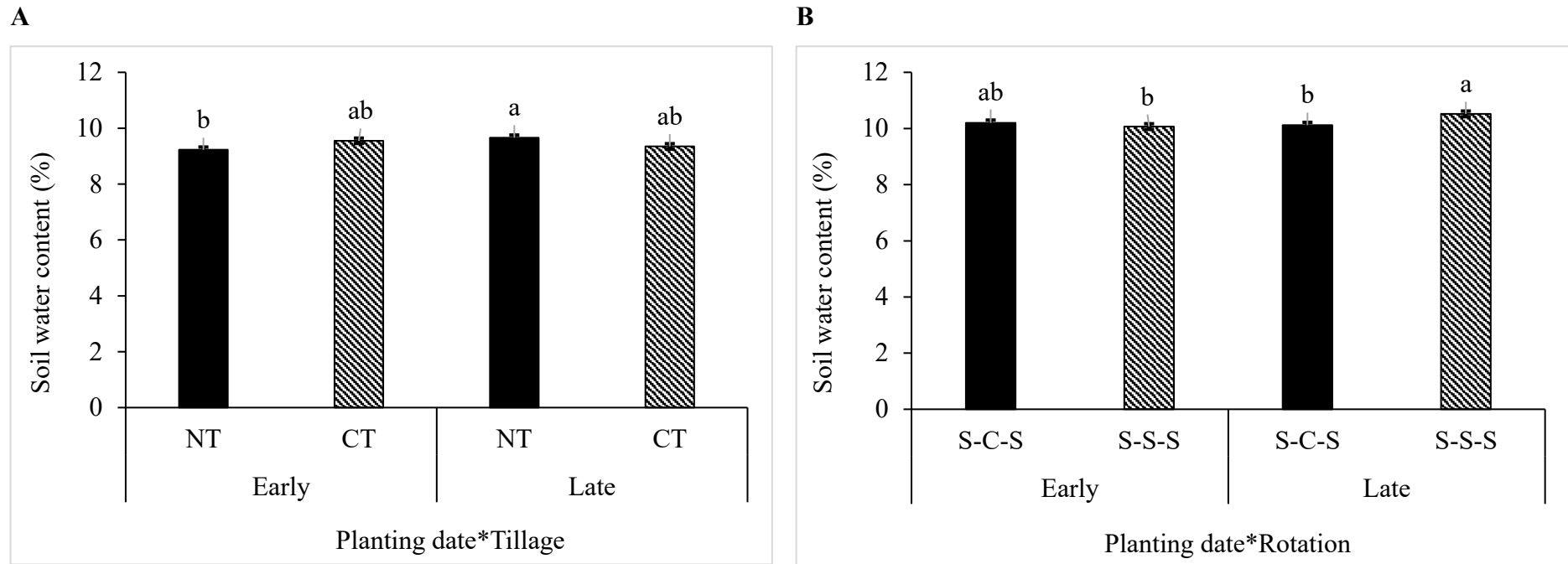


Figure 4.3: Soil water content as affected by the interaction of planting date and tillage during summer (April 2023) (A), and the combination of planting date and rotation during winter (June 2023) (B), in season three at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

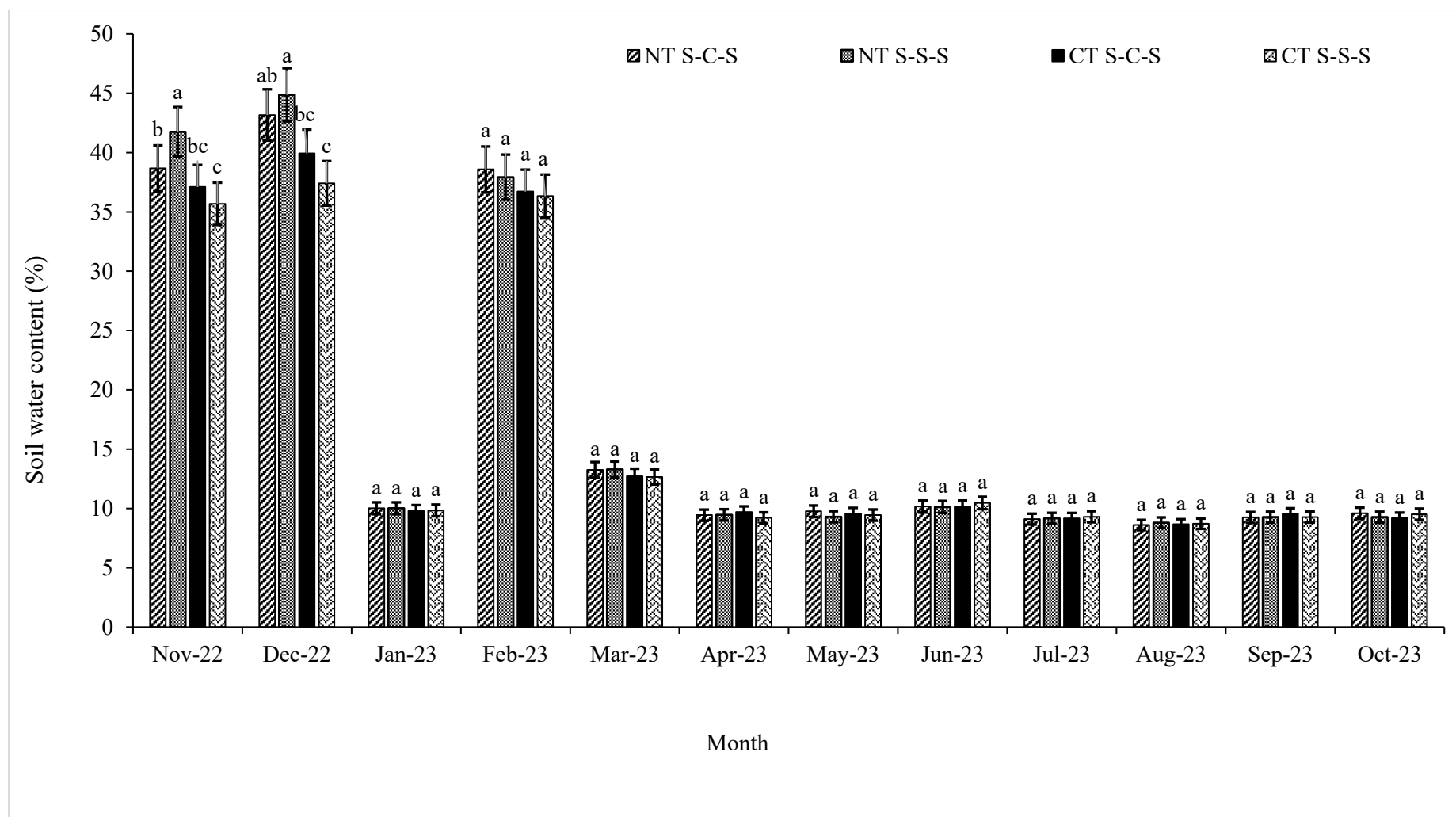


Figure 4.4: Mean monthly soil water content as affected by the interaction of tillage and rotation in season three at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

Effects of planting date, tillage and rotation on soil water content at Clau-Clau

At Clau-Clau, planting date, crop rotation and their interactions including planting date x rotation and planting date x tillage x rotation did not significantly influence soil water content throughout season three (Table 4.2). However, tillage had significant effects; the CT treatment significantly improved soil water content compared to NT during both dry months (2021/22) and wet month in 2022 (Table 4.2). No-tillage (NT) had a significantly lower soil water content ranging from 9.97 – 30.3% in dry months (2021/22). During the wet month of 2022, soil water content remained lower under NT compared to CT (1.90 and 3.20%, respectively) (Figure 4.5). When late planting was combined with NT, soil water content was significantly higher than late planting × CT, early × CT and early planting × NT (4.91, 3.79, 4.11 and 3.68%, respectively) in wet month specifically in Jun 2022 (Figure 4.6). Surprisingly, this trend reversed in July 2022, when late planting × NT decreased soil water content by more than double compared to late planting × CT and early planting × CT in wet month (July) in 2022 (Figure 4.6). The interaction between tillage and rotation significantly decreased soil water content with at least 8.74% significantly lower soil water content with the interaction of NT and S-S-S than under NT and S-C-S and both rotations under CT during dry month in 2022 (Figure 4.7).

Table 4.2: p-value of planting date, tillage and rotation, as well as interactions on soil water content at Clau-Clau in season three.

Treatment	df	Nov-21	Dec-21	Jan-22	Feb-22	Mar-22	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22
p-value of soil moisture													
PD	1	0.6172	0.4287	0.4630	0.3147	0.1446	0.4623	0.6922	0.0668	0.7355	0.5596	0.3082	0.8241
Tillage	1	0.0134*	0.7181	0.7923	0.2551	0.1435	0.0011*	0.0028*	0.1650	0.0065*	0.1609	0.3324	<.0001*
Rotation	1	0.1706	0.9293	0.5231	0.9213	0.3192	0.5991	0.1972	0.3182	0.2307	0.4315	0.0577	0.4473
PD*Tillage	1	0.8395	0.9047	0.6364	0.4594	0.6285	0.4835	0.8950	0.0020*	0.0230*	0.7540	0.5946	0.7095
PD*Rotation	1	0.1971	0.3801	0.8327	0.0662	0.7166	0.8954	0.8950	0.8084	0.3287	0.6717	0.7071	0.5669
Tillage*Rotation	1	0.3001	0.9096	0.6520	0.5586	0.9751	0.9277	0.8064	0.9955	0.2262	0.0058*	0.4434	0.6864
PD*Tillage*Rotation	1	0.3647	0.8077	0.7023	0.1427	0.3750	0.8241	0.9429	0.5389	0.3345	0.9853	0.9127	0.5052

Note: df – degree of freedom; PD – planting date.

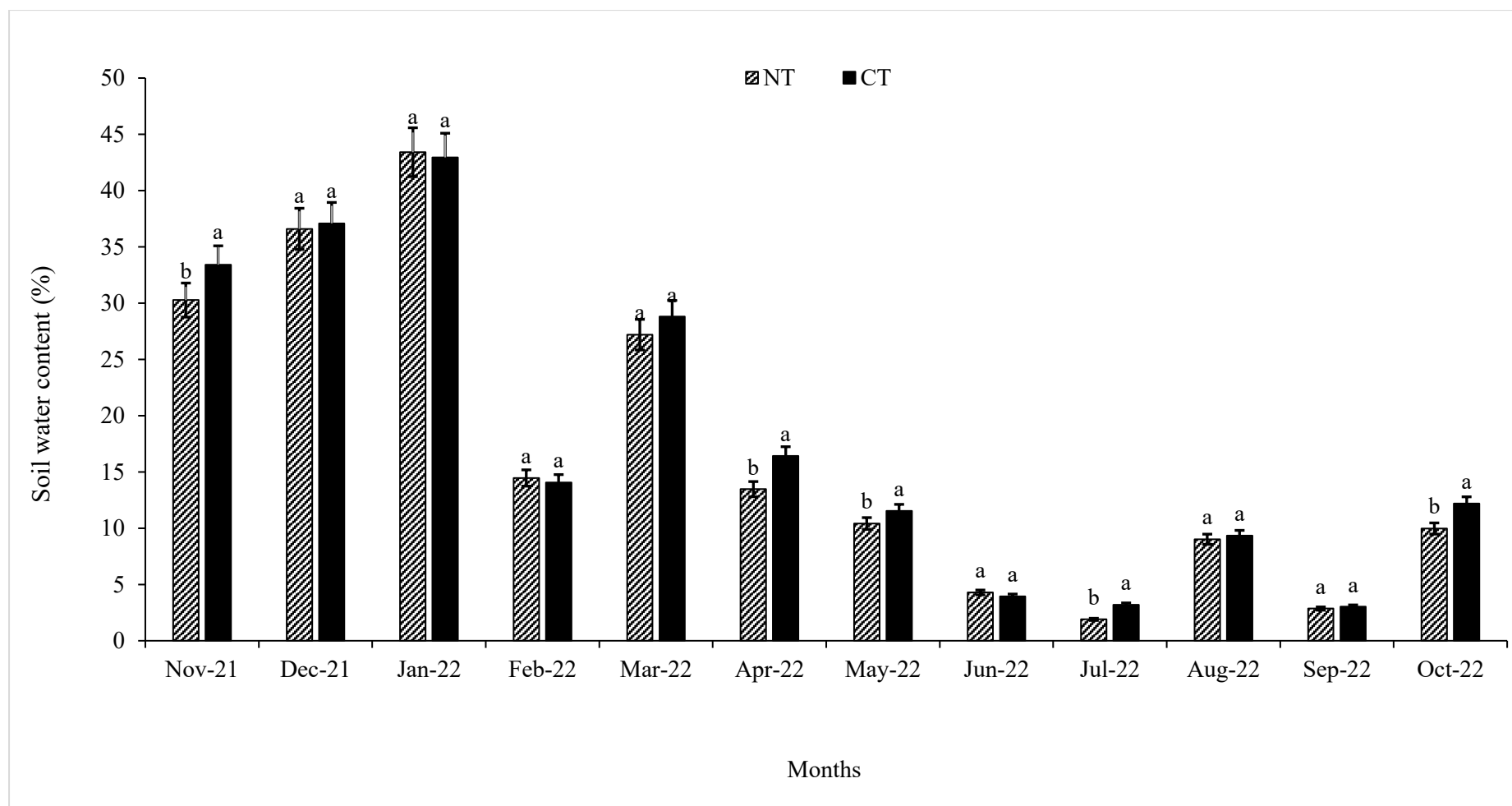


Figure 4.5: The interaction of tillage and crop rotation effects on soil water content measured over time in season three at Clau-Clau experimental site. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

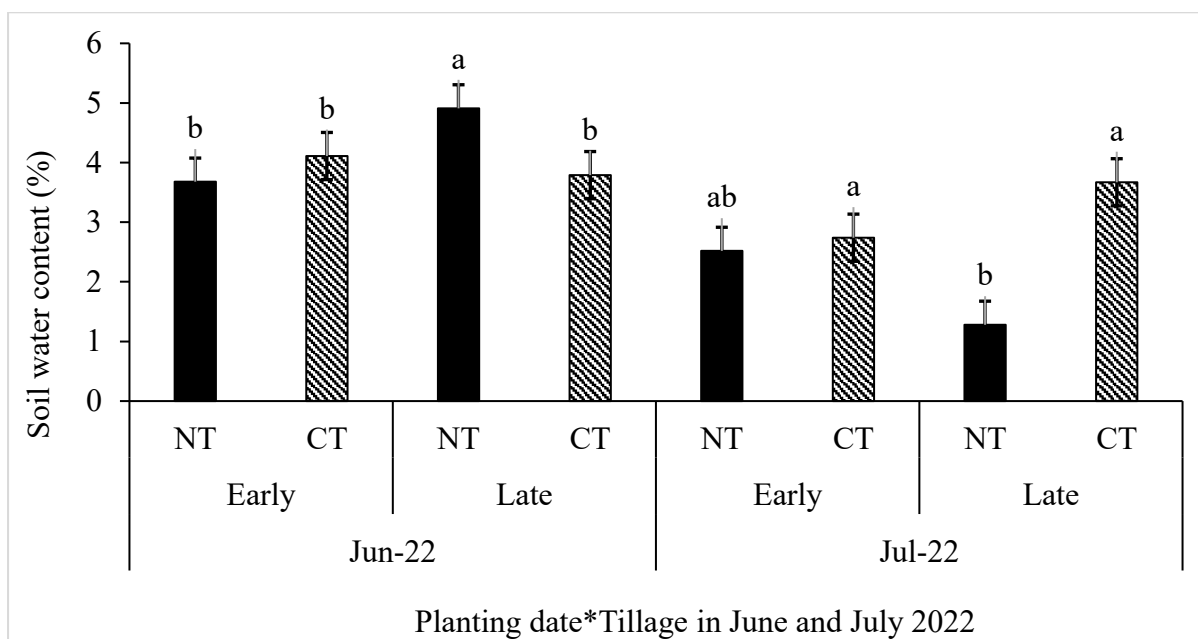


Figure 4.6: The combination effects of planting date and tillage on soil water content during winter in season three at Clau-Clau. Difference letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

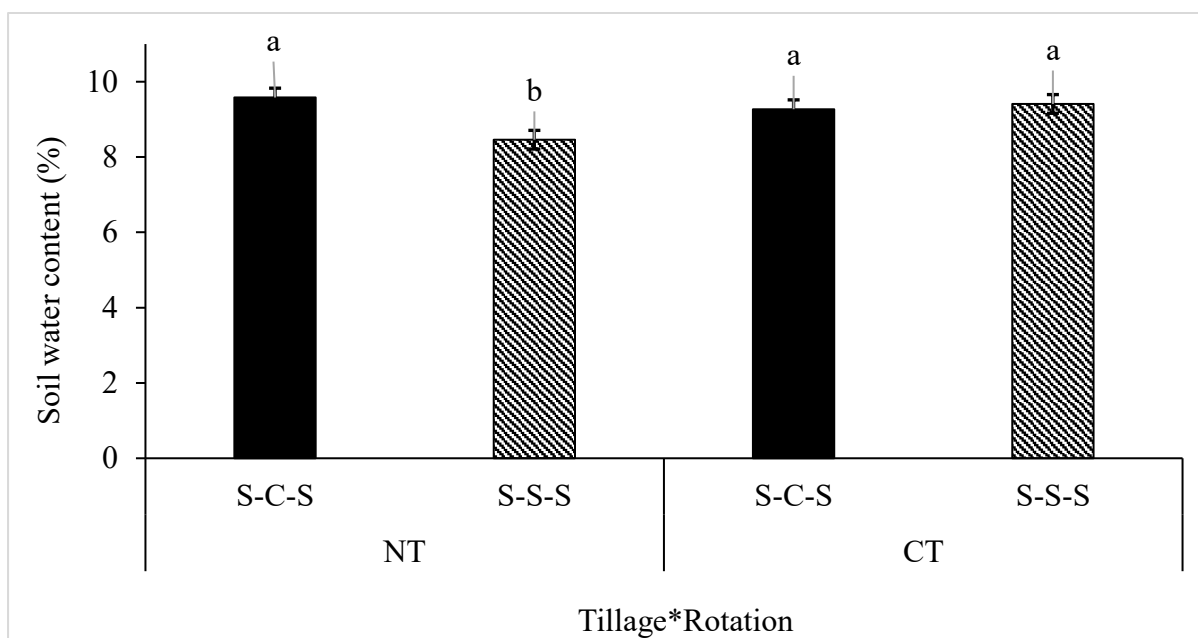


Figure 4.7: Interaction impacts of tillage and rotation on soil water content in August 2022 in season three at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum and S-S-S – sorghum-sorghum-sorghum; Bars represent standard error.

4.4.2. Soil organic carbon (SOC) as affected by planting date, tillage and rotation

Distinct patterns in how management practices influenced SOC were observed across the two seasons at Mphanama and Clau-Clau. Consistently, SOC was not significantly improved by the three-way interaction of planting date, tillage and crop rotation at the end of season two and season three at both sites (Table 4.3). Generally, the SOC in season three was higher than in season two, suggesting that there was a slight build-up of SOC between the two seasons.

At Mphanama, planting date was the only management factor that significantly enhanced SOC in both seasons, with late planting resulting in a 22.0% increase in SOC during season two, and a 17.5% increase in season three when compared to early planting (Table 4.4; Table 4.5). Neither tillage nor crop rotation, nor any of their interactions, significantly influenced SOC content at Mphanama in either season (Table 4.3).

In contrast, at Clau-Clau, planting date did not significantly improve SOC in either season. Instead, tillage system had a highly significant effect on SOC in both growing seasons (Table 4.3). No-tillage (NT) consistently led to higher SOC content than CT, increasing SOC by 39.5% in season two and 34.8% in season three (Table 4.4; Table 4.5). Crop rotation also played a role at Clau-Clau, though its effect was season-dependent. Crop rotation significantly increased SOC only in season two, where the S-C-S rotation had significantly higher SOC compared to S-S-S rotation (Table 4.4). Surprisingly, crop rotation did not affect SOC in season three. Furthermore, a significant tillage by rotation interaction was observed in season two at Clau-Clau. The combination of NT and S-C-S (resulted in a significantly greater SOC compared to NT $\times$ S-S-S, CT $\times$ S-C-S and CT $\times$ S-S-S (0.60, 0.41, 0.39 and 0.37%, respectively) in season two at Clau-Clau (Figure 4.8).

Table 4.3: p-value of planting date, tillage, rotation as well as interactions on SOC in season two and three for both sites.

Treatment	df	SOC	
		Season two	Season three
Mphanama			
Planting date	1	0.012*	0.044*
Tillage	1	0.461	0.127
Rotation	1	0.401	0.859
Planting date*Tillage	1	0.334	0.312
Planting date*Rotation	1	0.866	0.498
Tillage*Rotation	1	0.726	0.741
Planting *Tillage*Rotation	1	0.846	0.741
Clau-Clau			
Planting date	1	0.511	0.218
Tillage	1	0.001*	0.001*
Rotation	1	0.016*	0.894
Planting *Tillage	1	0.566	0.054
Planting *Rotation	1	0.925	0.218
Tillage*Rotation	1	0.003*	0.283
Planting *Tillage*Rotation	1	0.859	0.283

Note: df – degree of freedom.

Table 4.4: Effects of planting date, tillage and rotation on SOC at Mphanama and Clau-Clau study sites at the end of season two (2021/22 and 2020/21, respectively).

Treatment	Mphanama	Clau-Clau
	SOC (%)	SOC (%)
Planting date		
Early	0.41b	0.47a
Late	0.50a	0.44a
p-value	p<0.05	ns
Tillage		
NT	0.44a	0.53a
CT	0.46a	0.38b
p-value	ns	p<0.05
Rotation		
S-C-S	0.47a	0.50a
S-S-S	0.44a	0.40b
p-value	ns	p<0.05

Note: Different letters (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; S-C-S – Sorghum-cowpea-sorghum; S-S-S –sorghum-sorghum-sorghum; SOC – soil organic carbon.

Table 4.5: Effects of planting date, tillage and rotation on SOC at Mphanama and Clau-Clau sites at the end of season three (2022/23 and 2021/22, respectively).

Treatment	SOC (%)	
	Mphanama	Clau-Clau
Planting date		
Early	0.63b	0.56a
Late	0.74a	0.52a
p-value	p<0.05	ns
Tillage		
NT	0.66a	0.62a
CT	0.72a	0.46b
p-value	ns	p<0.05
Rotation		
S-C-S	0.69a	0.54a
S-S-S	0.68a	0.54a
p-value	ns	ns

Note: Different letters (a and b) – significant differences ($p<0.05$); ns – no significant; NT – no-tillage; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; SOC – soil organic carbon.

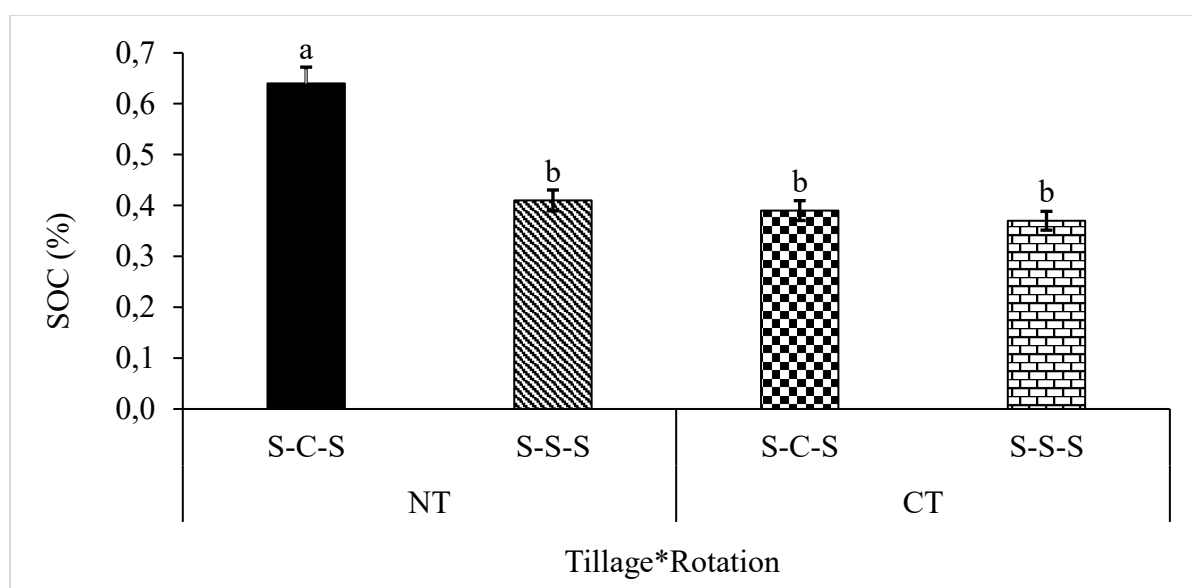


Figure 4.8: Tillage and rotation interaction effects on SOC at the end of season two (2020/21) at Clau-Clau. Different letters (a and b) – significant differences ($p<0.05$); NT – no-tillage; CT

– conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; SOC – soil organic carbon; Bars represent standard error.

4.4.3. Effects of planting date and tillage on soil protein

The responses of soil protein to management practices differed between Mphanama and Clau-Clau. Overall, the main factors, i.e. planting date and tillage as main factors did not significantly enhance soil protein at either site or across the seasons (Table 4.6). At Mphanama, while none of the treatment or interaction has significant effects on soil protein (Table 4.6). The soil protein generally increased significantly with each successive season (Figure 4.9). This increase as seasons progressed at Mphanama, resulted higher soil protein at the end of season three than end of season one (0.73 and 0.38 mg g⁻¹, respectively) (Figure 4.9), indicating a substantial build-up of soil protein over time irrespective of planting date or tillage. The combination of planting date and tillage significantly increased the soil protein in season two at Clau-Clau (Table 4.6). During this season, the combination of early planting with NT (0.35 mg g⁻¹) and that of late planting with CT (0.36 mg g⁻¹) resulted in higher soil protein compared to the combination of early planting with CT (0.28 mg g⁻¹) and that between late planting and NT (0.29 mg g⁻¹) at the end of season two at Clau-Clau (Figure 4.10).

Table 4.6: p-value of planting date and tillage as well as the interaction on soil protein in season two and three at both sites

Treatment	df	Soil protein	
		Season two	Season three
Mphanama			
Planting date	1	0.201	0.134
Tillage	1	0.953	0.875
Planting date*Tillage	1	0.824	0.888
Clau-Clau			
Planting date	1	0.691	0.187
Tillage	1	0.824	0.506
Planting *Tillage	1	0.013*	0.169

Note: df – degree of freedom.

Table 4.7: Effects of planting date and tillage on soil protein at Mphanama site at the end of season one, and season two, and season three after harvest.

Treatment	Season one	Season two	Season three
Soil protein (mg g ⁻¹)			
Planting date			
Early	0.36a	0.66a	0.93a
Late	0.40a	0.41a	0.53a
p-value	ns	ns	ns
Tillage			
NT	0.37a	0.54a	0.75a
CT	0.39a	0.53a	0.71a
p-value	ns	ns	ns

Note: ns – no significant; NT – no-tillage; CT – conventional tillage.

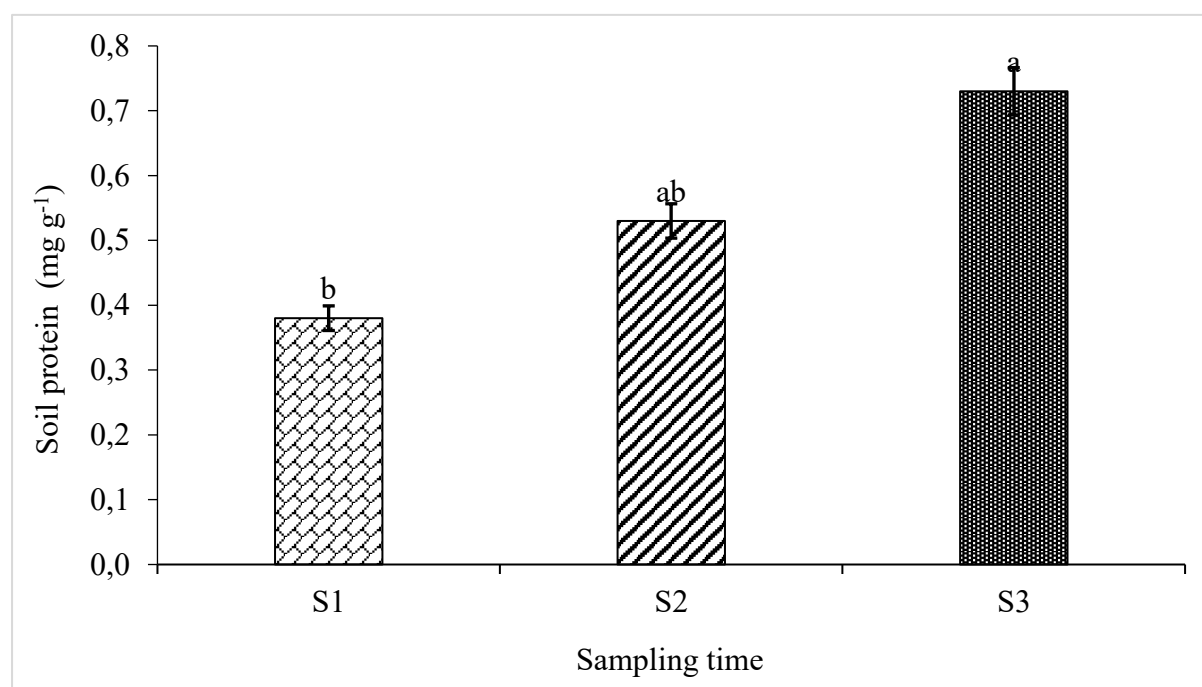


Figure 4.9: Soil protein over sampling time (S) at Mphanama. Different letters (a and b): significant differences ($p < 0.05$); S1 – end of season one; S2 – end of season two; S3 – end of season three; Bars represent standard error.

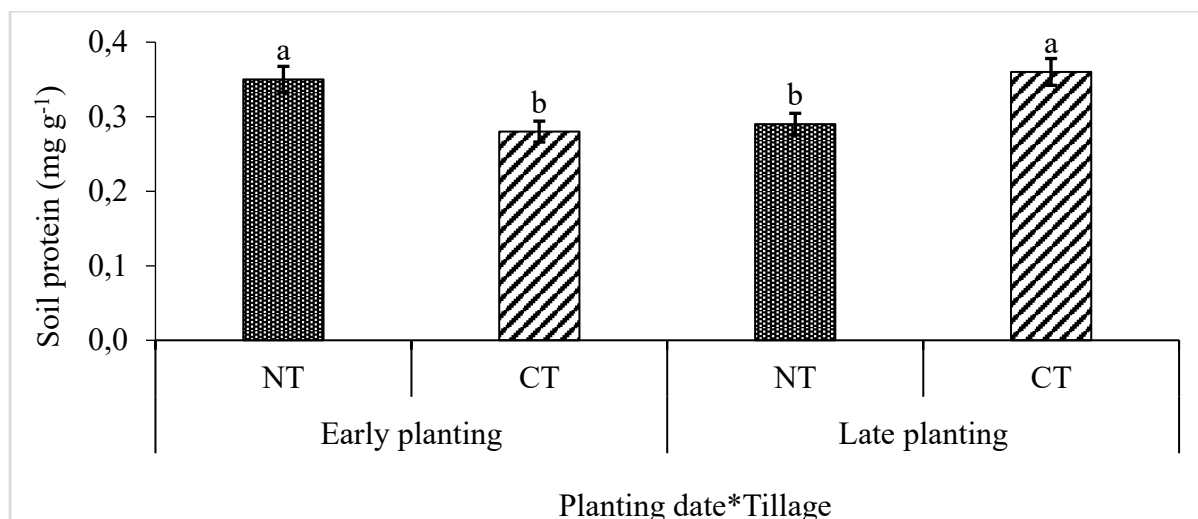


Figure 4.10: Effects of the interaction of planting date and tillage on soil protein at the end of season two at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – conventional tillage; Bars represent standard error.

Table 4.8: Effects of planting date and tillage on soil protein at Clau-Clau site at the end of season one, season two and season three after harvest.

Treatment	Season one	Season two	Season three
Soil protein (mg g ⁻¹)			
Planting date			
Early	0.29a	0.31a	0.30a
Late	0.34a	0.32a	0.26a
p-value	ns	ns	ns
Tillage			
NT	0.34a	0.32a	0.29a
CT	0.29a	0.32a	0.27a
p-value	ns	ns	ns

Note: ns – no significant; NT – no-tillage; CT – conventional tillage.

4.4.4. Effects of planting date, tillage and crop rotation on the SOC fractions

Planting date significantly improved fine POC at Mphanama, while tillage significantly increased all the measured soil POC fractions at Clau-Clau (Table 4.9). At Mphanama, fine

POC fraction was significantly higher under late planting compared to early planting (0.09 and 0.07%, respectively) after three years (Table 4.10). After three years, tillage and rotation as main factors and when dates of planting interacted with tillage and rotation, did not significantly improved soil POC across all measured fractions at Mphanama (Table 4.9). Conversely, at Clau-Clau, planting date and rotation had no significant effects on the POC fractions (Table 4.9). However, NT significantly increased all measured soil POC fractions, NT significantly enhanced all these fractions compared to CT (Table 4.9). No-tillage had 53.9%, 117% and 100% higher MAOC, fine POC and coarse POC, respectively, compared to CT at Clau-Clau after three years of the study (Table 4.11). MAOC contributed the highest proportion of SOC accumulation, followed by fine POC, and coarse POC fraction contributing the least (Table 4.11).

Table 4.9: p-value of planting date, tillage, rotation, and the interactions on SOC fractions at Mphanama and Clau-Clau at the end of season three.

Treatment	df	Coarse POC	Fine POC	MAOC
Mphanama				
Planting date	1	0.864	0.038*	0.567
Tillage	1	0.819	0.781	0.543
Rotation	1	0.868	0.896	0.396
Planting date*Tillage	1	0.195	0.079	0.180
Planting date*Rotation	1	0.658	0.894	0.624
Tillage*Rotation	1	0.976	0.548	0.183
Planting date*Tillage*Rotation	1	0.682	0.764	0.346
Clau-Clau				
Planting date	1	0.842	0.228	0.228
Tillage	1	0.003*	0.003*	<.0001*
Rotation	1	0.301	0.200	0.603
Planting date*Tillage	1	0.143	0.070	0.334
Planting date*Rotation	1	0.349	0.531	0.098
Tillage*Rotation	1	0.369	0.095	0.818
Planting date*Tillage*Rotation	1	0.411	0.882	0.088

Note: df – degree of freedom; MAOC – mineral-associated organic carbon; POC – particulate organic carbon.

Table 4.10: Effects of tillage and rotation on SOC fractions at the end of season three of the study at Mphanama.

Treatment	Coarse POC (%)	Fine POC (%)	MAOC (%)
Planting date			
Early	0.026a	0.072b	0.478a
Late	0.027a	0.093a	0.450a
p-value	ns	p<0.05	ns
Tillage			
NT	0.025a	0.081a	0.478a
CT	0.027a	0.084a	0.445a
p-value	ns	ns	ns
Rotation			
S-S-S	0.027a	0.083a	0.443a
S-C-S	0.026a	0.082a	0.485a
p-value	ns	ns	ns

Note: Different letters in the column (a and b) – significant differences ($p<0.05$); ns – not significant; NT – no-tillage; CT – conventional tillage; S-S-S – sorghum-sorghum-sorghum; S-C-S – sorghum-cowpea-sorghum; MAOC – mineral-associated organic carbon; POC – particulate organic carbon.

Table 4.11: Effects of tillage and rotation on SOC fractions at the end of season three of the study at Clau-Clau.

Treatment	Coarse POC (%)	Fine POC (%)	MAOC (%)
Planting date			
Early	0.018a	0.063a	0.312a
Late	0.019a	0.051a	0.337a
p-value	ns	ns	ns
Tillage			
NT	0.024a	0.078a	0.394a
CT	0.012b	0.036b	0.256b
p-value	p<0.05	p<0.05	p<0.05
Rotation			
S-S-S	0.017a	0.050a	0.330a
S-C-S	0.020a	0.064a	0.320a
p-value	ns	ns	ns

Note: Different letters in the column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; S-S-S – sorghum-sorghum-sorghum; S-C-S – sorghum-cowpea-sorghum; MAOC – mineral-associated organic carbon; POC – particulate organic carbon.

4.5. Discussion

The higher soil water content observed under late planting and NT could be attributed to the slightly higher dry matter yield under late planting which could be positively influenced by the improvement of SOC under late planting in semi-arid of this study. Higher biomass production results in higher leaf development, which shade the soil surface, thus minimizing direct sunlight on the soil surface. Moreover, the retention of mulch under NT might have resulted in greater soil water retention than CT, which had no mulch in this study. Higher soil water content observed for the interaction between NT and late planting and when sorghum monoculture was planted late could also be explained by the higher dry matter yield which was increased under late planting. The higher soil water content observed under NT as a main factor and when NT interacted with continuous sorghum at Mphanama, was likely due to minimum soil disturbance

and higher sorghum crop biomass production, resulting in greater water infiltration and lower evaporation losses. For instance, biomass production under the combination of NT and continuous sorghum was 29% higher than NT with sorghum-cowpea rotation at Mphanama. In this study the NT treatment was coupled with retention of mulch while the mulch was absent under CT. The lower soil water content with sorghum-cowpea-sorghum rotation compared to continuous sorghum could be due to limited cowpea biomass production which was exacerbated by the extreme drought conditions. The higher soil water content under NT aligns with findings by Bekele et al. (2022), who found higher soil water content under NT treatments and explained that using improved water infiltration rate under conservation tillage. Extreme drought conditions are among the major challenges affecting crop growth and production, especially under semi-arid regions in southern Africa. For instance, Foster et al. (2018) observed failure of sorghum grain production due to extreme or severe drought conditions in a 5-year cotton-grain sorghum rotation. While sorghum did not completely fail due to its drought tolerance, the low productivity of cowpea in this study contributed to low biomass input. In addition, the observed poor production of cowpea as affected by high temperatures and rapid decomposition of cowpea residues in these sandy soils reduced the mulching effects, leading to increased evaporation and runoff losses in this study.

Other studies have demonstrated positive effects of crop residue retention under NT systems in dryland agriculture, where soil water content was higher with mulch retention compared to CT without mulch (Verhulst et al., 2011; Baumhardt et al., 2012). In the current study, soil water content was consistently greater in the NT than CT plots in November and December 2022 at Mphanama, suggesting the important role NT plays in maintaining soil water in sandy soils, during the rainy season. However, some studies have reported higher soil water content under CT than NT, potentially because of the variations in soil types and differences of rainfall received between sites (Obalum et al., 2012; Acharya et al., 2019). Thus, advantages of NT in terms of soil water content appears to be more pronounced in the drier (semi-arid) area of Mphanama than in the wetter (sub-humid) area of Clau-Clau. The higher soil water content observed under CT at Clau-Clau (sub-humid), could be influenced by ploughing which might have improved soil properties such as bulk density and water infiltration rate. Although there were no differences in dry matter yield between NT and CT at Clau-Clau (Chapter 3; Mabasa et al. 2025), the retention of mulch under NT was expected to result in greater soil water retention than CT with no mulch. However, the amount of mulch produced ($<2 \text{ t ha}^{-1}$) may not have been significantly high enough to influence moisture retention. These findings agreed

with the findings observed by Acharya et al. (2019) who reported 7.9% and 4.3% higher soil water content in 0 – 15 and 15 – 30 cm depths, respectively, in the CT than NT systems in soils dominated by sandy loam. The higher soil water content observed under the combination of early planting and CT compared to late planting and NT was likely due to the higher dry matter yield when early planting interacted with CT (2.80 t ha^{-1}) than late planting and NT (2.22 t ha^{-1}). The results can also be explained by the higher plant height under the interaction of early planting and CT (107 cm) than NT under late planting (102 cm), in season three at Clau-Clau. Taller plants have higher biomass and leaf area which improves water retention by minimizing evaporation, while ploughing could have improved soil physical properties such as decreased bulk density. While the combination of late planting and NT in June 2022 could have improved soil water content due to the absence of intensive ploughing and retention of crop residues, which could have minimized evaporation. The lower soil water content observed under the interaction of NT and S-S-S compared to the other interactions was likely due to the lower biomass production. For instance, the interaction of NT and S-S-S had a lower mean dry matter yield of 2.26 t ha^{-1} compared to NT and S-C-S (2.36 t ha^{-1}), CT and S-S-S (2.94 t ha^{-1}), and CT and S-C-S (2.60 t ha^{-1}). Moreover, the interaction of NT and S-S-S had a lower mean crop height of 101 cm compared to NT and S-C-S (105 cm), CT and S-S-S (106 cm), and CT and S-C-S (108 cm). The differences observed between the two sites could be derived by the variations in soil properties, rainfall distribution patterns as well as climatic conditions.

The differences in soil water content could not be explained by the results of SOC at both study sites. While NT had higher soil water content than CT, the SOC values were not significantly different between the tillage systems, at Mphanama. Conversely, CT had lower SOC but had higher soil water content than NT at Clau-Clau. While there were these differences, the SOC levels were too low ($<1.0\%$) in all the treatment combinations to influence soil water content. Despite similar soil textures at both sites, with Mphanama having 6% clay (92% sand) and Clau-Clau having 8% clay (88% sand), the differing climate conditions could have led to contrasting results. The results show that the effects of NT on soil water content are more evident under drier and warmer conditions of Mphanama while Clau-Clau with wetter conditions appeared to benefit more from CT. Clau-Clau is generally wetter and cooler, therefore higher soil water addition with lower evaporation, reducing the benefits of the mulch. Mphanama was drier and warmer, higher potential evaporation rate, and mulch (NT) becomes much more important.

The higher SOC observed with late than early planting at Mphanama could be attributed to the combination of lower rainfall levels received after December and reduced decomposition rates of SOM by soil microbes. In contrast, higher rainfall can wash away soil particles with SOC, leading to possible soil quality degradation (Nwite, 2022). The lack of differences in SOC and its fractions, including soil protein, between NT and CT at Mphanama could be influenced by low biomass addition under the warmer and drier conditions, which limited SOC accumulation in these sandy soils. However, at Clau-Clau, higher SOC and its different fractions, in the NT plots at the end of season 2 and 3, was likely because of the crop residue left on the soil surface and the absence of intensive ploughing. The higher soil water content and warmer conditions under CT could have accelerated the decomposition of SOC compared to NT, which had lower soil water content and potentially cooler conditions caused by the mulch at Clau-Clau. These findings align with previous research that showed higher SOC under NT than under tilled treatments (Tian et al., 2016; Zhang et al., 2017). The higher SOC observed over time at Clau-Clau highlights the benefits of consistently practising NT. The variation in the amount of SOC, with higher SOC in season two, but not significantly different between rotations at the end of season three could be attributed to the inherent properties of sandy soils. Sandy soils have larger pores spaces, which enhance oxygen availability and water permeability, thereby supporting microbial life and activity. Under these conditions, SOC becomes more accessible to soil microorganisms, accelerating decomposition and mineralization processes. Consequently, this increased microbial activity can lead to greater SOC turnover, potentially offsetting long-term SOC accumulation despite initial gains under NT.

Generally, NT or reduced tillage with crop residue input promotes higher SOC accumulation compared to CT because of rapid decomposition of SOM, possibly because of exposure of soil aggregate protected C and an increase in soil microbial activity under CT (Borie et al., 2006; Paye et al., 2024). Observed lower accumulation of SOC in the coarse POC and fine POC fractions compared to the MAOC fractions could be attributed to the higher amounts of sand and lower clay in the soil (Table 3.1), which could have limited soil aggregation at the Clau-Clau study site. The observed results contradict those reported by Yao et al. (2023), who reported higher SOC accumulation in the coarse POC (>2 mm) and fine POC fractions than in the MAOC fractions, which could be influenced by a slightly higher clay content (15%) in a sandy loam soil compared to the 8% clay content in the sandy soil from Clau-Clau.

At Mphanama, the higher fine POC under late planting is consistent with total SOC observations, suggesting that SOC levels improved under low rainfall levels in sandy soils. However, the lack of significant difference in POC as a result of interaction of tillage and rotation at Mphanama, corresponded with the results of total SOC, which showed a lack of significant effects of tillage (NT vs CT systems) and rotation (sorghum monoculture and sorghum – cowpea), potentially due to limited biomass input and the low clay content. For instance, crop production was low in the second growing season due to extreme high temperatures, which might have limited SOC accumulation and improvement at Mphanama. These findings agreed with the results reported by Bhattacharyya et al. (2009), who found that crop rotation did not significantly affect POC within the 0 – 30 cm soil depth, regardless of the tillage treatments in a sandy clay loam in a 4-years study in a sub-temperate region, with an average daily temperature ranging from 31.7 and 20.6 °C in summer and 17.8 to 1.1 °C in winter. This lack of tillage effect was also observed on soil protein after three years of the study at Mphanama. The soil protein contributes to soil aggregation, and the aggregate protected SOC includes the soil protein. The short period of the study (3 years) could not offer any meaningful impact of crop rotation on POC in this nature of sandy soils with less than 1% SOC and less than 10% clay content in both study sites. However, the general increase in the soil protein concentration over the three-year period, irrespective of treatment, suggests that the production of sorghum under the different systems, increased this parameter over time. These findings suggest the need for additional management strategies, such as incorporating organic amendments such as manure to further improve these soil properties in sandy soils over a longer period.

The lack of effects of planting date and tillage on soil protein within each sampling period at Mphanama, could potentially be due to limited biomass additions on these sandy soils under low rainfall conditions, in addition to the study's limited duration. The findings of this current study contradict the results reported by Singh et al. (2018), who found that NT with crop residue retention significantly increased the soil protein after 3 years in soils dominated by sandy loam texture. Furthermore, the observed significant increase of soil protein over time, nearly doubling from year two to year three, which could be attributed to tillage benefits within the soil and temperature variations, showed that the production of sorghum has a potential to increase soil aggregation, but treatment effects may require more longer termed studies. The higher soil protein with early planting date under NT at Clau-Clau, could be influenced by higher biomass additions coupled with minimum soil disturbance. The higher soil protein

observed when sorghum was planted later under CT than NT could be clearly explained that it could be due to tillage creating favourable soil conditions for soil microorganisms responsible for soil protein production.

The variation in SOC between sites highlights the site-specific effects of tillage and planting dates, with tillage influencing SOC at Clau-Clau and planting date impacting SOC at Mphanama. The Mphanama site is drier and received lower rainfall than Clau-Clau during the study period, potentially resulting in lower biomass additions. For instance, the mean dry matter was lower at Mphanama (2.04 t ha^{-1}) compared to Clau-Clau (2.41 t ha^{-1}) in season 3 (Chapter 3: Table 3.3; Table 3.7). The higher SOC and its fractions under NT, especially with early planting and S-C-S rotation, suggest that this practice will enhance soil fertility compared to CT at Clau-Clau but not at Mphanama. However, the soil fertility benefits, from the increased labile SOC fractions, occurs at the expense of soil water content, which follows the opposite trend at Clau-Clau.

4.6. Conclusion

The findings of this study highlight the importance of site-specific management practices for optimising soil quality in dryland cropping systems on sandy soils. At Mphanama, NT and the combinations of NT with either continuous sorghum or sorghum-cowpea rotation improved soil water content but not SOC and its fractions in the sandy soils of this drier site. The interaction of NT and S-S-S improved soil water content at Mphanama. When sorghum in monoculture was planted late at Mphanama, this resulted in higher soil water content, while CT under both early and late planting improved soil water content under sub-humid conditions at Clau-Clau. However, soil moisture was improved at both sites when sorghum was planted late under NT. At Clau-Clau, continuous ploughing improved soil water content, while NT significantly enhanced SOC levels and its POC fractions, especially with sorghum-cowpea rotation and early planting. These findings suggest that NT practices and sorghum-cowpea rotation are beneficial for enhancing SOC and POC at Clau-Clau, while late planting could help improve SOC in sandy soils and within the fine POC fraction at Mphanama. The benefits of NT on soil water content were more evident in the drier, warmer conditions at Mphanama, while wetter and cooler conditions which favoured CT at Clau-Clau. Given the short duration of this study, long-term impacts of crop rotation on soil health remain inclusive. Therefore,

further research should focus on long-term studies and the integration of organic amendments, like manure in order to improve properties of sandy soils. Adopting NT, adjusting planting dates and exploring long-term rotation strategies may offer sustainable solutions for smallholder farmers under rainfed agriculture in regions with very low and poor rainfall distribution.

5.0. THE SHORT-TERM RESPONSE OF SOIL MICROBIAL COMMUNITIES TO PLANTING DATE AND NO-TILLAGE PRACTICE ON SANDY SOIL UNDER SEMI-ARID AND SUB-HUMID CLIMATE IN SOUTH AFRICA

5.1. Abstract

Intensive ploughing coupled with the removal of crop residues on sandy soils worsens the poor accumulation of soil organic carbon (SOC), with deleterious effects on functions of soil microbial communities, especially in arid areas. This study investigated the impact of tillage and planting date on activities of selected soil enzymes and microbial community functional diversity under contrasting climatic conditions. The short-term (3 years) study was conducted in sandy soils with <1.0% SOC and <10% clay content under two contrasting climatic conditions at Mphanana (semi-arid) and Clau-Clau (sub-humid) villages located in Limpopo and Mpumalanga Provinces, respectively. A randomized complete block design (RCBD), set up in a strip-plot treatment structure was used. The tillage treatments were no-tillage (NT) and conventional tillage (CT), while planting date treatments were early and late planting. Tillage did not significantly affect both β -glucosidase and acid phosphomonoesterase activity in both season two and three at both sites. Late planting increased acid phosphomonoesterase activity by 44.0% compared to early planting in season three at Mphanama. Tillage did not significantly affect the Shannon index (H) and microbial evenness (E), but NT decreased the microbial richness (R) and average well colour development (AWCD) by 35.8% and 43.4%, respectively than CT in season two at Mphanama. In season three of the study, late planting had 36.8% and 73.0% higher microbial richness (R) and AWCD index, respectively at Mphanama. No-tillage increased the microbial evenness (E) by 3.03% than CT, while CT increased the AWCD index by 25.9% than NT in season three at Mphanama. At Clau-Clau, late planting improved the AWCD by 26.1% than early planting while NT significantly increased the AWCD by 21.3% compared to CT in season two of the study. None of the treatments affected any of the microbial diversity indices in season three at Clau-Clau. The AWCD index was positively correlated to carbohydrate, amino acid, amine and polymer, while the microbial richness (R) was correlated to carboxylic acids at late planting under CT in season three at Mphanama. At Clau-Clau, polymer positively correlated with H and R, while the AWCD index correlated with

carbohydrates at early plating under CT in season three. These observations suggest that adopting site-specific management practices should be tailored to local soil conditions and climatic factors and the results will be useful in guiding the adoption of soil conservation management.

Keywords: Functional diversity, microbial biomass, planting date, soil enzymes, tillage.

5.2. Introduction

Intensive ploughing, insufficient precipitation and high temperatures, coupled with crop residue removal on sandy soils negatively affect soil organic carbon (SOC) accumulation. Soil microorganisms rely on SOC as a substrate and source of energy, and as such the soil microbial composition and function are profoundly connected to the concentration of SOC (Tang et al., 2023). Soil microorganisms are important in the maintenance of soil health and are involved in the recycling of soil nutrients by transforming SOM through decomposition, which increases their availability to plants (Ko et al., 2017; Li et al., 2021; Medo et al., 2021). The rapid response of soil microbial community diversity and activity to environmental and human induced factors make them sensitive indicators of soil quality (Wang et al., 2017). For instance, soil enzymes have been used as important indicators of soil quality in soil biological assessments. The most frequently used soil enzymes are β -glucosidase, urease and phosphatase for carbon (C), nitrogen (N) and phosphorus (P) cycling, respectively (Gil-Sotres et al., 2005; De Varennes and Torres, 2011).

Climate change alters the soil microbial community diversity, population and function and as such any resulting changes or shifts significantly affect soil quality and the sustainability of crop yield (Khmelevtsova et al., 2023). These effects may be more pronounced in sandy soils, that store less SOC (a substrate for soil microbes) and soil water than clayey soils, as the soil enzymes are sensitive to environmental factors (Caravaca et al., 2002). Management strategies that improve SOC could be beneficial in increasing soil water storage, maintaining optimum temperatures, and recycling nutrients through soil microbial activity. The response of soil microbial community diversity and enzyme activity have been studied in comparison between conventional and NT agricultural systems. Dong et al., (2017) reported that, the NT system with straw cover had higher of SOC content and created a favourable environment (soil water

content and temperature), which improved soil microbial diversity, compared to soil under intensive ploughing. Mina et al. (2008) demonstrated that continuous NT systems significantly increased carbohydrates from 3.1 to 4.9 mg g⁻¹ and alkaline phosphatase from 9.3 to 74.6% compared to CT in a 3-year study in a sandy clay loam soil. Their study also found that the CT practice significantly increased cellulase activity from 31 to 75% compared to NT. However, Acosta-Martinez et al. (2011) demonstrated that β -glucosidase and phosphatase activities were not affected by zero tillage and CT after 5 years under grain sorghum rotation, in a dryland cropping system under semi-arid climate. Conversely, Wozniak (2019) found higher activities of dehydrogenases and phosphatases under a CT compared to NT within 2 years in a sandy clay soil.

The inconsistencies in these results were related to the variations in SOC content, types of soil and climatic conditions. For instance, Acosta-Martinez et al. (2011) conducted their study under semi-arid conditions, with sandy loam soil containing 0.65 g kg⁻¹ SOC while Wozniak's study was under soil dominated by a sandy clay texture with a mean SOC of 6.61 g kg⁻¹ and 580 mm of annual precipitation. These factors (SOC, other soil factors and climate) are vital for the functioning and the community of soil microorganisms. Furthermore, the addition of crop residues, depending on crop type (e.g., biomass production and C/N ratio), and soil types, significantly influences soil microbial activity (Liu et al., 2016). Crop diversification in CA systems is very important considering the current state of climate change.

The CA system has been successfully adopted by large scale commercial farmers in Australia, central Brazil and America, it is hardly adopted by smallholder farmers in developing countries (Lal, 2007; Kassam et al., 2019). Baudron et al. (2012), demonstrated that most research-based evidence on the positive effects of CA is not based on field experiments but on controlled experiments (on station) which have received higher amounts of inorganic inputs which boost the production of crop biomass to a large extent. Thus, controlled experiments such as in the greenhouses, do not experience some of the natural and environmental constraints like when trials are conducted in the field under a natural environment (Ngwira et al., 2012). In Africa, getting smallholder farmers to use crop residues as mulch to protect and improve soil quality is challenging because the same crop residues are needed as fodder for domestic animals (Mchunu et al., 2011; Duncan et al., 2016). Thus, poor crop residues input influences the soil microbial activity and limits the quality of nutrient recycling in the soil, particularly in sandy

soils. As a result, agriculture sustainability becomes a serious challenge under dryland farming systems in marginal lands under rainfed agricultural systems.

With the ongoing negative effects of climate change, crops that are sensitive to drought often fail to reach maturity especially in semi-arid areas with sandy soils under rainfed farming systems, such as those found in parts of Limpopo province of South Africa. This highlights the need for conservation-based farming system, with drought tolerant crops, which will improve crop yields and agricultural sustainability in such areas. The use of sorghum, which is drought tolerant, may provide an opportunity for crop sustainability under rainfed conditions in areas with low precipitation, associated with climate change. The early (short-term) response of soil microbial community diversity and enzymatic activities, as affected by tillage and planting date under sorghum-based CA systems, may give potential insights into the effects of such practices over the long-term. There are limited studies reported in the literature on the short-term effects of these practices, particularly in sandy soils, where sorghum is grown under dryland conditions.

Therefore, the impacts of NT vs CT and planting date (early vs late planting) on enzymatic activities and soil microbial community functional diversity in a dryland farming system on sandy soils in Limpopo and Mpumalanga Provinces in South African were evaluated. The results of this study will advance knowledge on the trends of SOC transformation and nutrients cycling in the sorghum-based CA systems on sandy soils under dryland conditions under semi-arid and sub-humid conditions.

5.3. Materials and methods

5.3.1. Site description, experimental design and management

The details of the sites, experimental design, treatments and the management of non-experimental variables are described in Chapter three (Section 3.3.1 – 3.3.3). Soil sampling and method for analysis of the initial soil properties are described in Section 3.3.4 of Chapter three. The initial soil properties are presented in Chapter three (Table 3.1).

5.3.2. Soil sampling

Soil samples were randomly collected (0 – 30 cm soil depth) from 4 subplots (Figure 3.4) and mixed to make a composite sample. A total of 12 composite samples were used to test the effects of planting date and tillage as main factors on soil enzyme activities and microbial community functional diversity. The 4 plots selected for this study comprised of the combination of planting date and tillage, with plots under tillage made up of the combinations of cultivar and rotation (subplots) and were grouped together based on their similar tillage treatments (NT vs CT) according to the experimental design (Figure 3.4). While the experimental design included cultivar and rotation as subplot factors (Figure 3.4), their main effects were excluded from this particular analysis since previous assessments indicated they did not significantly influence the measured soil properties, crop growth, or yield parameters. The samples were immediately transferred into sealable plastic bags, placed in the cooler box, and transported to the laboratory, where they were stored in a refrigerator at -4°C, before further analyses took place.

5.3.3. Determination of β -glucosidase

The enzymatic activity of β -glucosidase was determined following a procedure described by Tabatabai (1994). Briefly, 1 g of sieved soil (< 2mm) was placed in a 50 mL flask to which 4 mL of a modified universal buffer (MUB) (pH 6.0) and 1 mL of 0.05 M p-nitrophenyl- β -D-glucoside (PNG) solution were added. The flask was swirled to mix the contents then stoppered before incubation at 37°C for 1 h. The reaction was terminated by adding a 1 mL of 0.5 M CaCl_2 and 4 mL of 0.1 M pH 12 tri (hydroxymethyl) aminomethane buffer solution. The suspension in the flask was allowed to develop a yellow colour then filtered. The intensity of the colour (absorbance) was determined by a UV/VIS spectrophotometer at 400 nm wavelength, and the concentration was calculated based on a standard curve that was developed before using standards. The β -glucosidase activity was reported on a dry soil basis with the units of mg p-nitrophenol kg^{-1} soil h^{-1} .

5.3.4. Determination of acid phosphomonoesterase

The analysis of acid phosphomonoesterase activity was done following a procedure described by Tabatabai (1994). A 1 g of freshly sieved (<2 mm) soil sample was transferred into 50 ml flask and 4 ml of modified universal buffer (MUB), 0.25 ml of volume and 1 ml of p-

nitrophenyl phosphate (p-NNP) solutions were added into the flask with the soil sample. The content was mixed and incubated at 37°C for 1 hr. A 1 ml of 0.5 M CaCl₂ and 0.5 M NaOH were added and mixed thoroughly. The soil was then removed by filtering the content through a Whatman filter paper (150 mm diameter). The absorbance of the filtrate fraction was done by using a UV/VIS spectrophotometer at 400 nm wavelength. Acid phosphomonoesterase activity was calculated after determining the mass of the p-nitrophenol produced based on a standard curve and corrected for the OD₄₀₀ of the blank followed by dividing the value by the equivalent dry weight of soil.

5.3.5. Determination of soil microbial functional diversity

Determination of soil microbial functional diversity was done using the Biolog C source utilization method (Chojniak et al., 2015). Before determination of functional diversity, a soil sample was homogenized by suspending it in saline buffer solution. A 150 µl was sampled from the aqueous suspension and placed into each of the different wells of a 96-well Biolog plate for each treatment. The plates were then incubated at 26°C for 1 week. Then, after optical density (OD) of each well was read on the Biolog MicroLog™ 3E system after every 24 hrs until constant readings were achieved, and the last reading being used for statistical analysis. Before analysis, each plate reading was normalized by subtracting the blank well value (control) from each plate well. The soil microbial response (total C source utilization) was quantified by the average well colour development (AWCD) from each well.

Thus, the AWCD was calculated by the following equation:

$$AWCD = \sum ODi / 31 \dots\dots\dots 2$$

where, ODi – optical density value from each well which was corrected by subtracting the blank well (inoculated without a C source) (Garland and Mills, 1991; Gomez et al., 2004).

The Shannon Wiener index (H) value (the richness and evenness) of the response of the soil microbial communities was calculated using the OD of 0.25 as a threshold for positive response, using the following equation:

$$H = - \sum p_i (\ln p_i) \dots\dots\dots 3$$

where, p_i – ratio of the activity on each substrate (OD_i) to the sum of activities on all substrates “ OD_i ”.

Shannon Evenness (E) index was calculated by the following equation:

$$E = H / \ln S \dots\dots\dots 4$$

where, H – Shannon wiener index; S – substrate richness.

Additionally, the specific utilization of the measured carbon sources was categorised into five functional groups (amine, amino acid, carbohydrate, carboxylic acid and polymer), according to Zak et al. (1994). The Biolog system detects the utilisation of specific C sources by bacteria from a set of 95 different C compounds on each of either Gram (-) or Gram (+) microplates (Biolog 1993). These, microplates are well designed to provide standardised biochemical tests for identifying a broad range of either Gram (-) or Gram (+) bacteria. The degree to which a particular substrate is utilised were quantified by measuring the intensity of colour change caused by incorporation of tetrazolium dye into a respiring bacterial community. For each group, the corrected absorbance values of the substrates were summarized and expressed as a percentage of total absorbance value of the plate (Weber and Legge 2009). These selected substrates (amine, amino acid, carbohydrate, carboxylic acid and polymer) have been successfully used to quantify the functional diversity of soil microbial communities and they are based on the community-level C sources utilisation patterns (Preston-Mafham et al., 2002).

5.3.6. Statistical analysis

Data of soil enzyme activities and microbial community functional diversity were analysed using analysis of variance (ANOVA) in JMP 16 Pro statistical software (SAS, 2021). Treatments means were separated using Fisher’s least significant difference (LSD) at a significant level of $p < 0.05$. The principal component analysis (PCA) was used to analyse the differences in the C source utilization profiles with relationships among variables visualised by plotting scores of their first two principal components in two dimensions (Juan and Zhang, 2015). PCA was used because it identifies the smallest number of linear functions of factors necessary to explain and visualise the maximum possible variance in the dataset (Grimm and Yarnold, 1995).

5.4. Results

5.4.1. Effects of planting date and tillage on soil enzymatic activities at both sites

Tillage and planting date as main factors and their interaction had no significant effect on β -glucosidase and acid phosphomonoesterase activities at the end of season two and three (Table 5.1; Table 5.2) at both sites, except that planting date significantly ($p < 0.05$) improved acid phosphomonoesterase activity at the end of season three at Mphanama (Table 5.1). Late planting had a significant higher phosphomonoesterase activity than early planting (50.4 and $35.0 \mu\text{g p-nitrophenol g}^{-1}$) in season three at Mphanama (Table 5.3). In the second and third seasons, β -glucosidase activity ranged from $10.8 - 12.9 \mu\text{g p-nitrophenol g}^{-1}$ soil and $35.0 - 35.4 \mu\text{g p-nitrophenol g}^{-1}$ soil respectively, irrespective of planting date and tillage at Mphanama (Table 5.2; Table 5.3). Acid phosphomonoesterase activity ranged from $83.2 - 85.2 \mu\text{g p-nitrophenol g}^{-1}$ soil in the second season and from $35.0 - 50.4 \mu\text{g p-nitrophenol g}^{-1}$ soil in the third season irrespective of planting date and tillage at Mphanama (Table 5.2; Table 5.3). At Clau-Clau, β -glucosidase activity ranged from $19.4 - 26.8 \mu\text{g p-nitrophenol g}^{-1}$ soil and $35.7 - 36.6 \mu\text{g p-nitrophenol g}^{-1}$ soil in the second and third seasons, respectively irrespective of planting date and tillage (Table 5.2; Table 5.3). While acid phosphomonoesterase activity ranged from $85.6 - 86.1 \mu\text{g p-nitrophenol g}^{-1}$ soil in season two and from $53.7 - 60.3 \mu\text{g p-nitrophenol g}^{-1}$ soil in season three irrespective of planting date and tillage at Clau-Clau (Table 5.2; Table 5.3).

Table 5.1: p-values of soil enzymatic activities as affected by planting date, tillage and the interactions at both sites

Treatment	df	p-value			
		β -Glucosidase	Acid phosph.	β -Glucosidase	Acid phosph.
Mphanama		Season two		Season three	
PD	1	0.260	0.150	0.938	0.018*
Tillage	1	0.438	0.359	0.811	0.243
PD * Tillage	1	0.730	0.875	0.677	0.465
Clau-Clau					
PD	1	0.815	0.798	0.523	0.601
Tillage	1	0.508	0.721	0.146	0.467
PD * Tillage	1	0.179	0.661	0.268	0.757

Note: df – degree of freedom; PD – planting date; Acid phosph – acid phosphomonoesterase activity.

Table 5.2: Effects of planting date and tillage on β -glucosidase and phosphomonoesterase activities at the end of season two at Mphanama and Clau-Clau

Treatment	Mphanama		Clau-Clau	
	β -Glucosidase ($\mu\text{g p-nitrophenol g}^{-1}$)	Acid phosph.	β -Glucosidase ($\mu\text{g p-nitrophenol g}^{-1}$)	Acid phosph.
Planting date				
Early	10.8a	85.2a	21.8a	86.1a
Late	12.9a	83.2a	24.4a	85.6a
p-value	ns	ns	ns	ns
Tillage				
NT	11.2a	83.6a	26.8a	86.1a
CT	12.5a	84.8a	19.4a	85.6a
p-value	ns	ns	ns	ns

Note: NT – no-tillage; CT – conventional tillage; ns – not-significance; Acid phosph. – acid phosphomonoesterase activity.

Table 5.3: Effects of planting date and tillage on β -glucosidase and phosphomonoesterase activities at the end of season three at Mphanama and Clau-Clau.

Treatment	Mphanama		Clau-Clau	
	β -Glucosidase ($\mu\text{g p-nitrophenol g}^{-1}$)	Acid phosph.	β -Glucosidase ($\mu\text{g p-nitrophenol g}^{-1}$)	Acid phosph.
Planting date				
Early	35.1a	35.0b	36.3a	59.2a
Late	35.2a	50.4a	35.9a	53.7a
p-value	ns	p<0.05	ns	ns
Tillage				
NT	35.4a	39.4a	35.7a	52.6a
CT	35.0a	46.0a	36.6a	60.3a
p-value	ns	Ns	ns	ns

Note: Different letters in the column (a and b) – significant differences (p<0.05); ns – not significance; NT – no-tillage; CT – conventional tillage; Acid phosph. – acid phosphomonoesterase activity.

5.4.2. Effects of planting date and tillage on soil microbial community diversity indices

The interaction between planting date and tillage did not significantly enhance Shannon's diversity index (H) and microbial evenness (E) (based on substrate utilisation) at the end of both season two and three at both sites (Table 5.4; Table 5.6). Planting date and tillage, as main factors, also did not significantly improve H and E (based on substrate utilisation) at both sites at the end of season two (Table 5.4). Compared to CT, R was significantly lower by 35.8% while AWCD was lower by 43.4% under NT in season two at Mphanama (Table 5.5). At Clau-Clau, NT significantly increased the AWCD than CT (1.14 and 0.94, respectively) during season two (Table 5.5). Planting date had no positive effects on any of the measured parameters at both sites except AWCD, which was greater under late planting than early planting (1.16 and 0.92, respectively), only at the end of season two at Clau-Clau (Table 5.5).

Planting date and tillage also did not improve any of the diversity indices at Clau-Clau, AWCD was nearly double under late planting than early planting (0.64 and 0.37, respectively) and it was greater under CT than NT (0.58 and 0.43, respectively), at Mphanama at the end of season

three (Table 5.7). The NT significantly increased E than CT (1.02 and 0.99, respectively), while the other parameters were not enhanced by tillage at Mphanama at the end of season three (Table 5.7). Late planting improved R by 36.8% over early planting, while NT had 3.03% higher E than CT, at the end of season three at Mphanama (Table 5.7).

Table 5.4: p-values of soil microbial diversity indices as affected by planting date, tillage and their interaction at the end of season two at both sites.

Treatment	df	p-value			
		H	R	E	AWCD
Mphanama					
Planting date	1	0.934	0.070	0.679	0.359
Tillage	1	0.442	0.016*	0.663	0.029*
PD * Tillage	1	0.449	0.718	0.615	0.923
Clau-Clau					
Planting date	1	0.101	0.079	0.573	0.017*
Tillage	1	0.297	0.260	0.263	0.050*
PD * Tillage	1	0.183	0.223	0.399	0.361

Note: df – degree of freedom; PD – planting date; H – Shannon diversity index; R – microbial richness; E – Species evenness; AWCD – Average well colour development.

Table 5.5: Soil microbial diversity indices at the end of season two as affected by planting date and tillage at both sites.

Mphanama					Clau-Clau			
Treatment	H	R	E	AWCD	H	R	E	AWCD
Planting date								
Early	2.57a	10.6a	1.04a	0.37a	3.12a	23.9a	0.99a	0.92b
Late	2.58a	14.6a	0.97a	0.46a	3.19a	26.1a	0.98a	1.16a
p-value	ns	ns	ns	ns	ns	ns	ns	p<0.05
Tillage								
NT	2.50a	9.83b	1.04a	0.30b	3.18a	25.7a	0.98a	1.14a
CT	2.65a	15.3a	0.98a	0.53a	3.13a	24.3a	0.99a	0.94b
p-value	ns	p<0.05	ns	p<0.05	ns	ns	ns	p<0.05

Note: Different letters in the column (a and b) – significant differences (p<0.05). ns – not significant; NT – no-tillage; CT – conventional tillage; H – Shannon diversity index; R – microbial richness; E – Species evenness; AWCD – Average well colour development.

Table 5.6: p-values of soil microbial diversity indices as affected by tillage, planting date and their interaction at the end of season three at both sites.

Treatment	df	p-value			
		H	R	E	AWCD
Mphanama					
Planting date	1	0.188	0.005*	0.151	0.0001*
Tillage	1	0.396	0.054	0.046*	0.029*
PD * Tillage	1	0.072	0.243	0.725	0.732
Clau-Clau					
Planting date	1	0.147	0.263	0.770	0.068
Tillage	1	0.624	0.707	0.150	0.308
PD * Tillage	1	0.533	0.707	0.560	0.273

Note: df – degree of freedom; PD – planting date; H – Shannon diversity index; R – microbial richness; E – Species evenness; AWCD – Average well colour development.

Table 5.7: Effects of planting date and tillage on soil microbial diversity indices at the end of season three at both sites.

Mphanama					Clau-Clau			
Treatment	H	R	E	AWCD	H	R	E	AWCD
Planting date								
Early	2.48a	13.6b	1.01a	0.37b	3.35a	30.1a	0.99a	1.62a
Late	2.79a	18.6a	1.00a	0.64a	3.31a	29.8a	0.98a	1.57a
p-value	ns	p<0.05	ns	p<0.05	ns	ns	ns	ns
Tillage								
NT	2.53a	14.4a	1.02a	0.43b	3.34a	29.9a	0.98a	1.58a
CT	2.73a	17.7a	0.99b	0.58a	3.32a	30.0a	0.99a	1.61a
p-value	ns	ns	p<0.05	p<0.05	ns	ns	ns	ns

Note: Different letters in the column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage; H – Shannon’s diversity index; R – Substrate richness; E – Substrate evenness; AWCD – Average well colour development.

5.4.3. Effects of planting date and tillage on soil microbial community diversity index as expressed by multivariate analysis / principal component analysis (PCA) at Mphanama and Clau-Clau

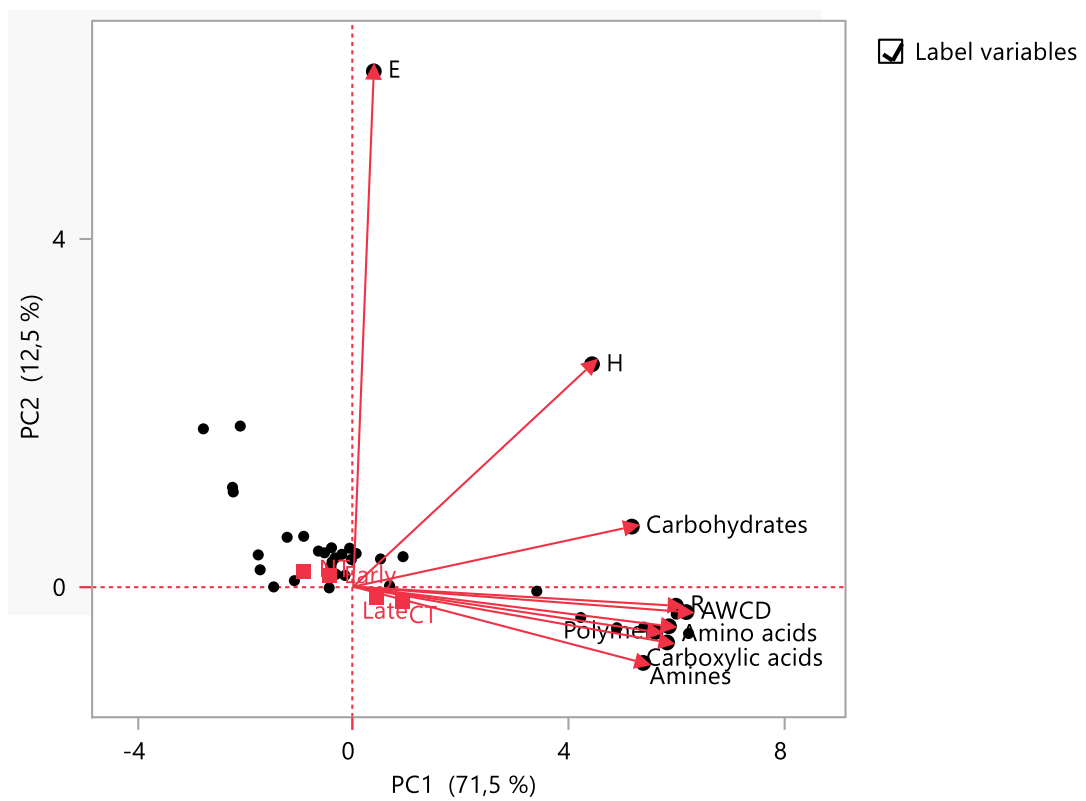
Over 80% of the variation of the soil microbial parameters was explained by two principal components (PCs) at Mphanama (PC1=71.5%; PC2=12.5%) and Clau-Clau (PC1=69.5%; PC2=11.5%) for season two (Figure 5.1A and Figure 5.1C, respectively). For season three, 72.2% at Mphanama (PC1=57.6%; PC2=14.6%) and 60.7% at Clau-Clau (PC1=45.1%; PC2=15.6%) were explained by two PCs (Figure 5.1B and Figure 5.1D, respectively). At both sites, both PC1 and PC2 effectively separated the effects of tillage and planting dates on microbial community functional diversity indices across seasons. In season two PC2 distinguished carbohydrates, Shannon Diversity (H) and substrate richness (E) from AWCD, R, amino acids, amines and carboxylic acids (Figure 5.1A). In season three, PC2 separated Carboxylic acids, R, H and E from amino acids, AWCD, amines, polymers and carbohydrates (Figure 5.1B). Early planting and NT had a weak or negative relationship with all measured microbial community diversity indices, while late planting and CT were the main drivers of measured microbial community diversity indices except for carbohydrates, H and E in season two at Mphanama. PCA showed that R and the AWCD indices, after season two, had positive

associations with the utilisation of amino acids, polymers, carboxylic acids and amines by soil microbes under CT with late planting at Mphanama (Figure 5.1A). At the same site, the AWCD index was positively associated to carbohydrates, amino acids, amines and polymers with late planting under the CT system at the end of season three (Figure 5.1B). Microbial richness (R) was positively associated to carboxylic acids at late planting under the CT system at the end of season three (Figure 5.1B).

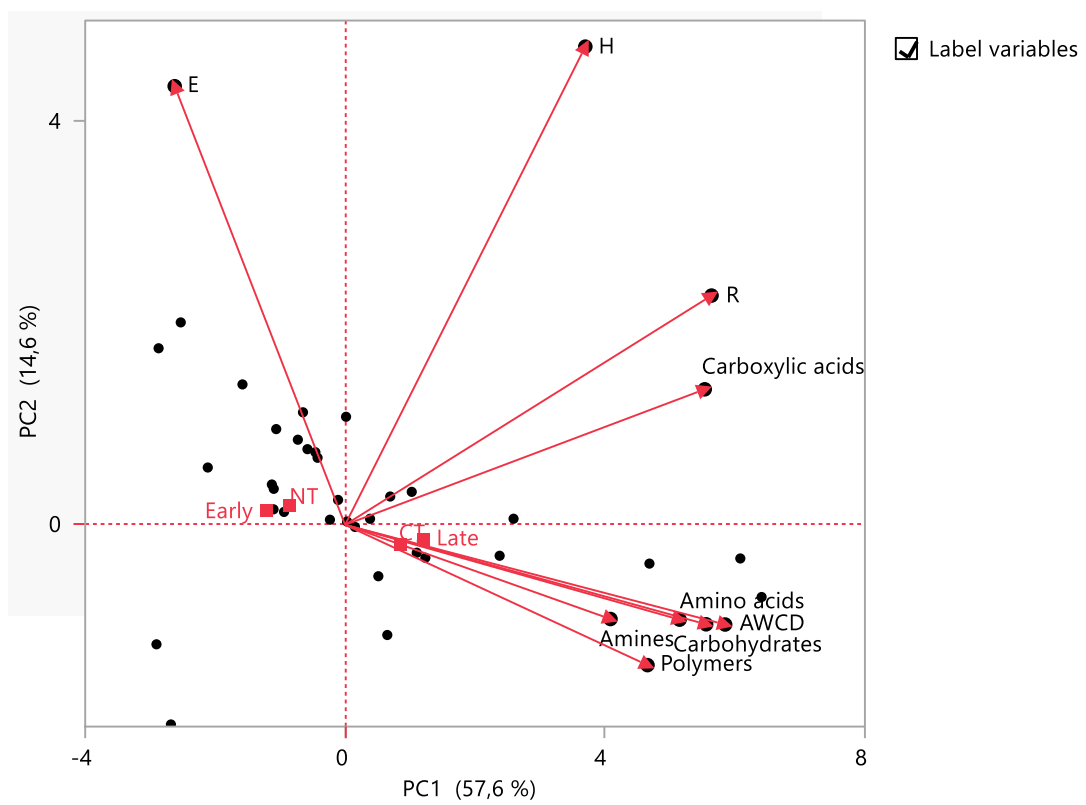
At Clau-Clau, PC1, in season two separated E from all other measured microbial community indices, influenced by CT and early planting, while amino acids, polymers amines and H were separated from AWCD, R carbohydrates and carboxylic acids (Figure 5.1C). The AWCD and R indices showed a positive relationship with carbohydrates and carboxylic acids utilisation under NT with late planting in season two at Clau-Clau (Figure 5.1C). In season three, PC1 indicated that late planting and NT were negatively associated with all microbial substrates, while PC2 separated amines, amino acids and R from AWCD, H, E, polymers, carbohydrates and carboxylic acids (Figure 5.1D). The AWCD index was associated with utilization of H and polymers at early planting under CT at the end of season three at Clau-Clau, while carbohydrates were positively associated with the utilisation of carboxylic acids and E (Figure 5.1D). Additionally, amines were positively correlated with amino acids at early planting under CT at the end of season three (Figure 5.1D).

The PC1 results showed that the separation effects were different across sites with PC1 and PC2 separated tillage and planting date in both sites but at Mphanama both growing seasons showed similar results trends, while at Clau-Clau the results trends differed across the growing seasons. At Mphanama, both late planting and CT were positively associated to microbial community diversity indices in both growing seasons, while at Clau-Clau late planting and NT were positively associated to the microbial community diversity indices in the second growing season, whereas during the third growing season, early planting and CT were positively related to the microbial community diversity indices.

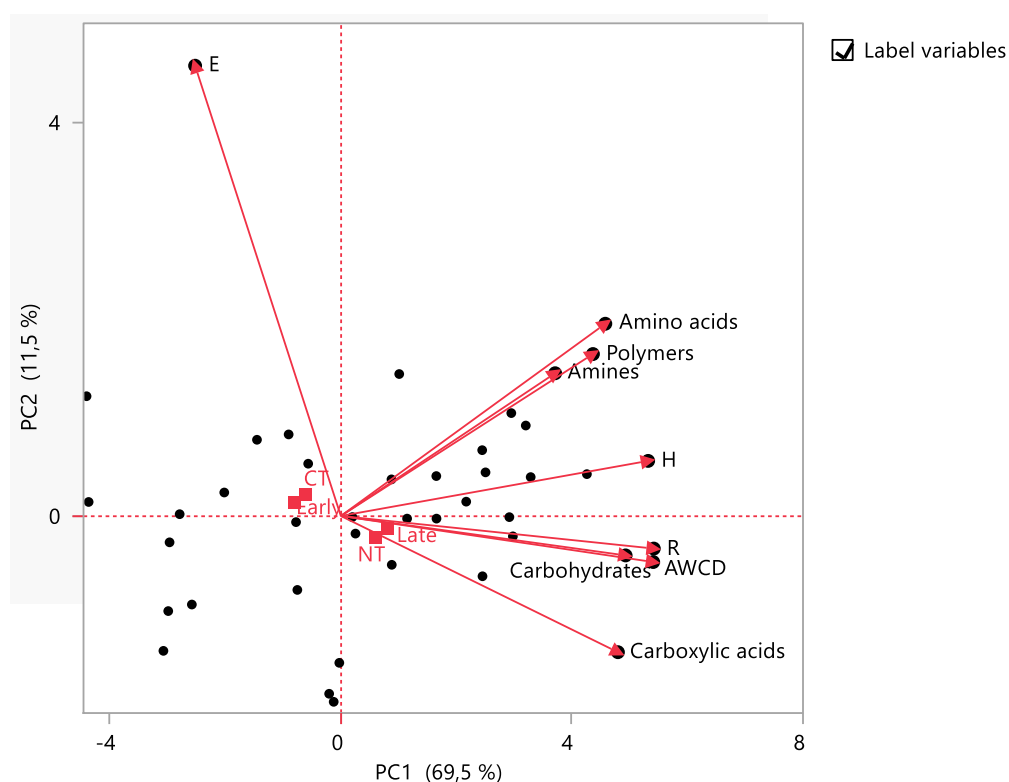
A



B



C



D

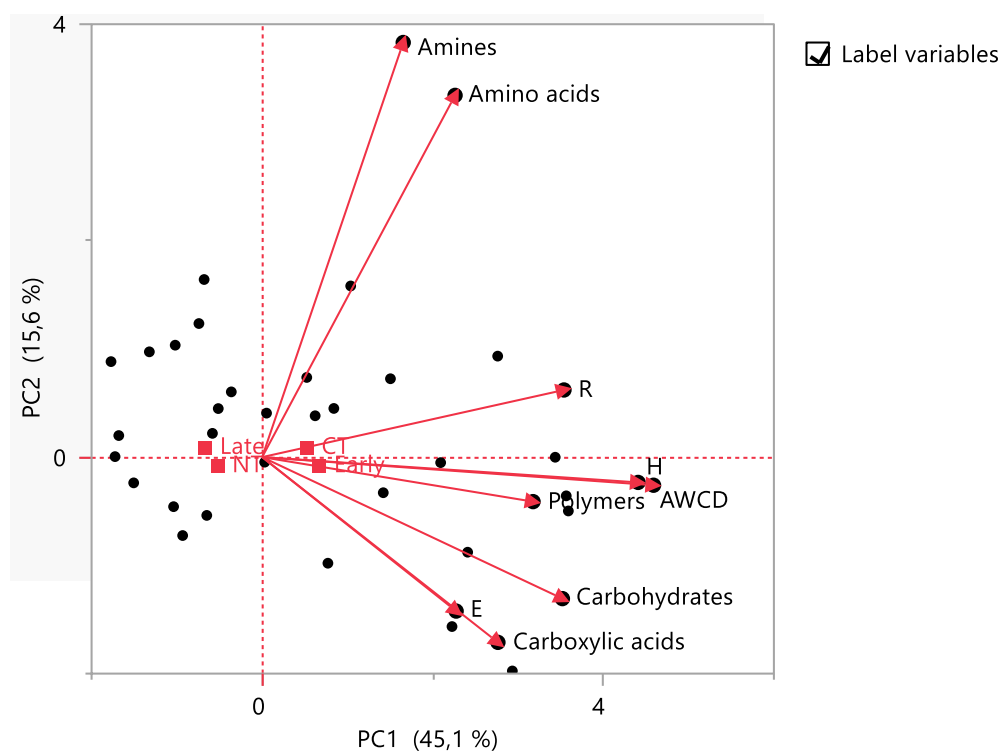


Figure 5.1: Effects of planting date and tillage on soil microbial community diversity expressed by Principal Component Analysis (PCA). A and B – PCA results after season two

and three, respectively at Mphanama. C and D – PCA results after season two and three, respectively at Clau-Clau. H – Shannon diversity index; R – Substrate richness; E – Substrate evenness; AWCD – Average well colour development.

5.4.4. Effects of planting date and tillage on soil microbial community functional diversity at Mphanama

Planting date as a main factor and when planting date interacted with tillage had no significant effects on the utilisation of all measured C sources in season two (Table 5.8). The combination of planting date and tillage also did not significantly improve all measured C sources in season three (Table 5.8). The observation of the results shows that CT had significantly higher utilisation of C sources compared to NT in season two. The CT significantly increased the utilisation of carboxylic acid than NT (0.46 and 0.15, respectively) at the end of season two (Figure 5.2). Conventional tillage also significantly increased the utilisation of amino acids and polymers by more than 100% and 55%, respectively compared to NT after season two (Figure 5.2). Amines were also significantly higher under CT than NT (0.42 and 0.09, respectively) at the end of season two (Figure 5.2). In season three, similar trend of results as in season two were observed, with CT significantly increasing soil microbial functional diversity compared to NT. The NT had significantly decreased the utilisation of carbohydrates, amino acids, polymers and amines by 19, 39, 31 and 80%, respectively than CT system at the end of season three (Figure 5.3). Planting date also significantly improved soil functional diversity, with late planting significantly increasing carbohydrates, carboxylic acids and polymers by 62, 48 and 163%, respectively compared to early planting at the end of season three (Figure 5.4).

Table 5.8: p-values of soil microbial community functional diversity as affected by tillage, planting date and their interactions at Mphanama in season two and three.

Treatment	df	p-value				
		Carbohydrates	Carboxylic acids	Amino acids	Polymers	Amines
Season two						
PD	1	0.631	0.566	0.244	0.081	0.495
Tillage	1	0.443	0.011*	0.011*	0.044*	0.037*
PD * Tillage	1	0.537	0.846	0.598	0.6960	0.566
Season three						
PD	1	<0.0001*	0.031*	0.108	<0.0001*	0.123
Tillage	1	0.043*	0.201	0.019*	0.038*	0.015*
PD * Tillage	1	0.628	0.921	0.996	0.216	0.349

Note: df – degree of freedom; PD – planting date.

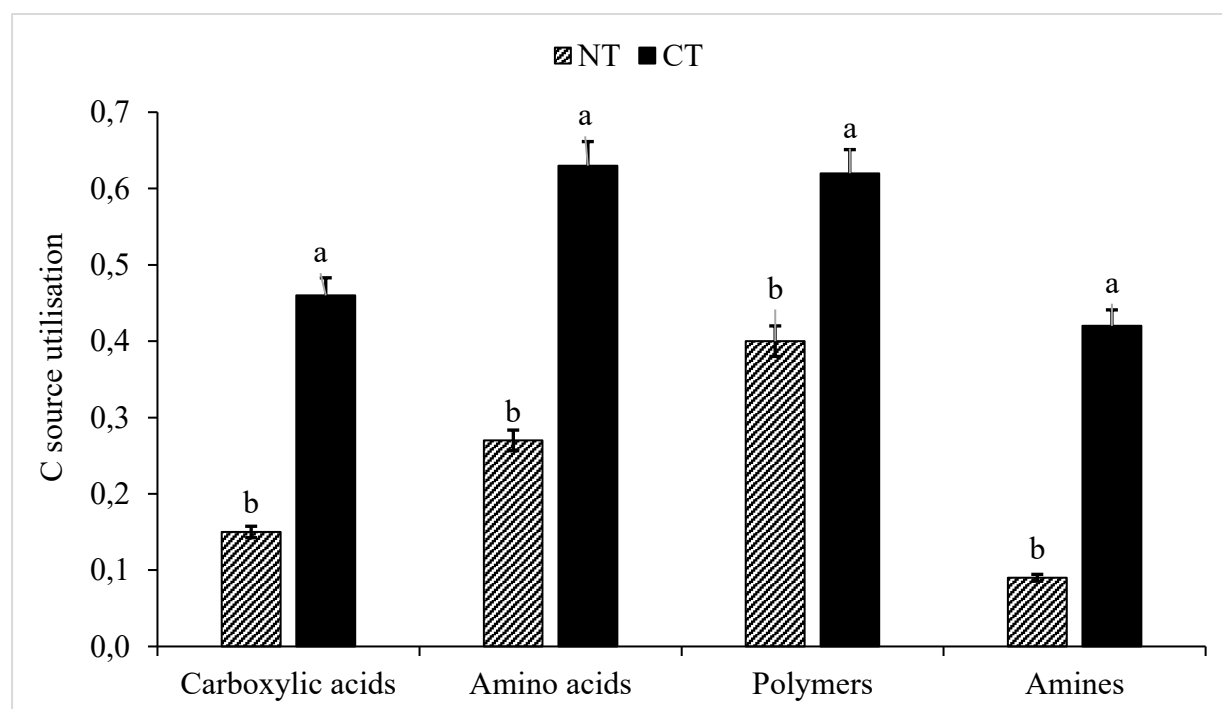


Figure 5.2: Effects of tillage on soil functional diversity at the end of season two at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – Conventional tillage; Bars represent standard error.

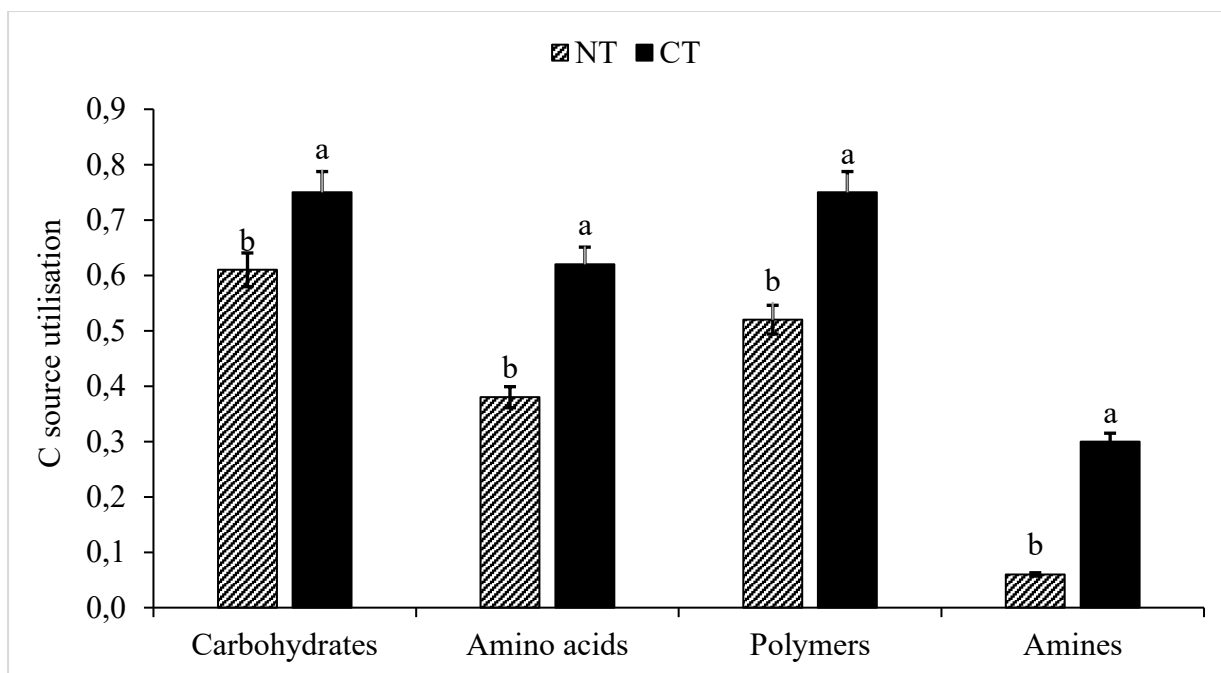


Figure 5.3: Effects of tillage on soil functional diversity at the end of season three at Mphanama experimental site. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – Conventional tillage; Bars represent standard error.

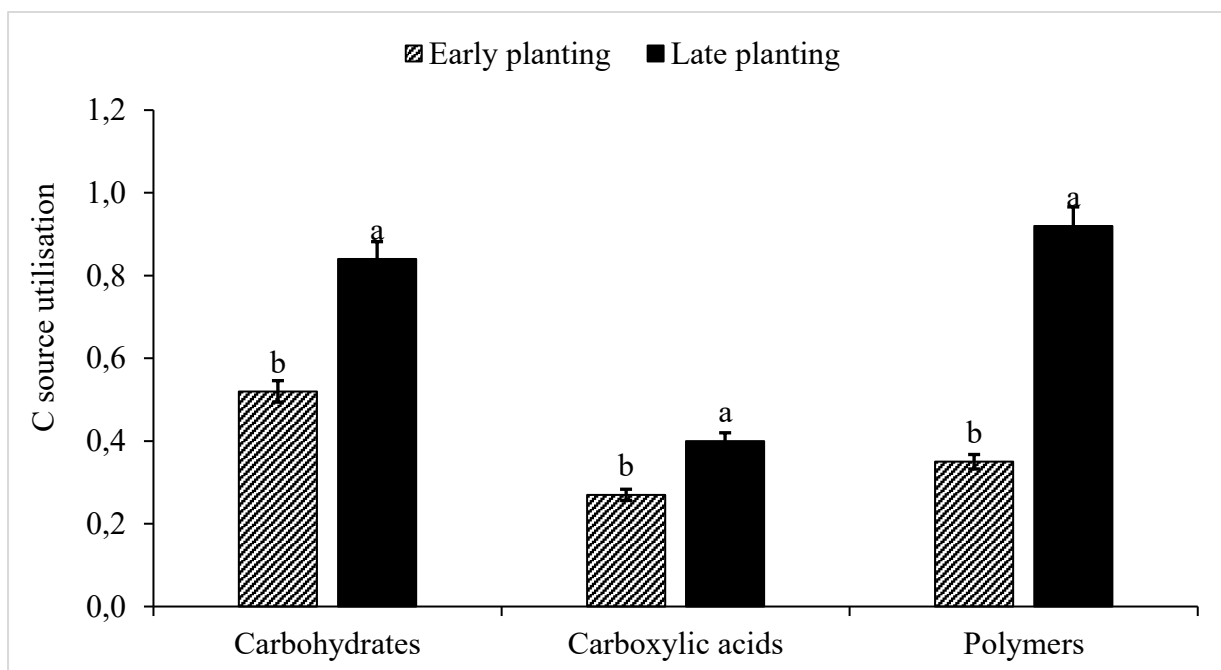


Figure 5.4: Effects of planting date on soil functional diversity at the end of season three at Mphanama. Different letters (a and b) – significant differences ($p < 0.05$); Bars represent standard error.

5.4.5. Effects of planting date and tillage on soil microbial community functional diversity at Clau-Clau

Planting date and tillage did not significantly affect amino acids, polymers and amines in season two (Table 5.9). Tillage significantly enhanced soil microbial functional diversity in season two, (Table 5.9). The NT significantly increased the utilisation of carbohydrates and carboxylic acids by 23.0 and 34.4%, respectively compared to CT at the end of season two (Table 5.10). Similar to tillage, planting date significantly increased the utilisation of carbohydrates and carboxylic acids at the end of season two (Table 5.9). In season three, tillage did not significantly improve carbohydrates, while planting date also did not improve amino acids (Table 5.9). Both planting date and tillage did not significantly enhance the utilisation of carboxylic acids, polymers and amines in season three. However, late planting increased the utilisation of carbohydrates by 19.3% and carboxylic acids by 43.3% compared to early planting in season two (Table 5.10). The combination of the time of planting and tillage significantly improved the soil carbohydrates at the end of season two, with late planting $\times$ NT significantly increasing the utilisation of carbohydrates by more than 43% compared to early planting $\times$ NT, early planting $\times$ CT and late planting $\times$ CT (Figure 5.5). At the end of season three, CT significantly increased amino acids by 3.98% than NT (Table 5.11). Planting date significantly increased the utilisation of carbohydrates, with higher carbohydrates observed under early planting than late planting (1.42 and 1.28, respectively) at the end of season three (Table 5.11). Moreover, this effect was further modified when planting date interacted with tillage. The combination of early planting $\times$ CT had over 17% higher carbohydrates compared to early planting $\times$ NT, late planting $\times$ NT and late planting $\times$ CT combinations during season three (Figure 5.6).

Table 5.9: p-values of soil microbial community functional diversity as affected by tillage, planting date and their interactions at Clau-Clau in season two and three.

Treatment	df	p-value				
		Carbohydrates	Carboxylic acids	Amino acids	Polymers	Amines
Season two						
PD	1	0.021*	0.001*	0.257	0.418	0.568
Tillage	1	0.008*	0.005*	0.749	0.163	0.950
PD * Tillage	1	0.016*	0.494	0.515	0.285	0.935
Season three						
PD	1	0.001*	0.963	0.524	0.683	0.609
Tillage	1	0.269	0.468	0.043*	0.371	0.414
PD * Tillage	1	0.039*	0.042*	0.180	0.230	0.574

Note: df – degree of freedom; PD – planting date.

Table 5.10: Effects of planting date and tillage on soil functional diversity at the end of season two at Clau-Clau.

Treatment	Carbohydrates	Carboxylic acids	Amino acids	Polymers	Amines
Planting date					
Early	0.88b	0.90b	1.17a	1.01a	0.64a
Late	1.05a	1.29a	1.30a	1.10a	0.76a
p-value	p<0.05	p<0.05	ns	ns	ns
Tillage					
NT	1.07a	1.25a	1.22a	1.13a	0.69a
CT	0.87b	0.93b	1.25a	0.97a	0.70a
p-value	p<0.05	p<0.05	ns	ns	ns

Note: Different letters in the column (a and b) – significant differences (p<0.05); ns – not significant; NT – no-tillage; CT – conventional tillage.

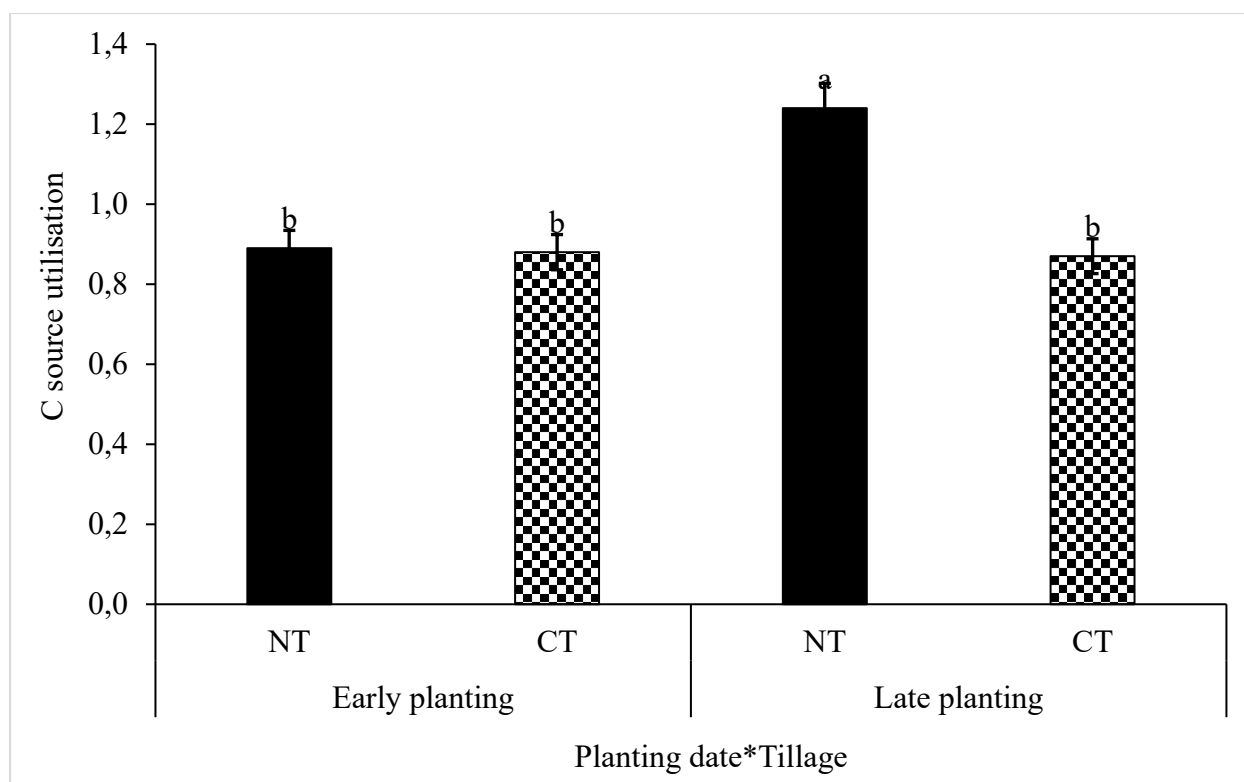


Figure 5.5: Interaction of planting date and tillage effects on the utilization of carbohydrates at the end of season two at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$) NT – no-tillage; CT – Conventional tillage; Bars represent standard error.

Table 5.11: Effects of planting date and tillage on soil functional diversity at the end of season three at Clau-Clau.

Treatment	Carbohydrates	Carboxylic acids	Amino acids	Polymers	Amines
Planting date					
Early	1.42 a	1.72a	1.80a	1.55a	1.75a
Late	1.28 b	1.71a	1.78a	1.52a	1.69a
p-value	$p < 0.05$	ns	ns	ns	ns
Tillage					
NT	1.33a	1.70a	1.76 b	1.57a	1.67a
CT	1.37a	1.73a	1.83 a	1.51a	1.77a
p-value	ns	ns	$p < 0.05$	ns	ns

Note: Different letters in the column (a and b) – significant differences ($p < 0.05$); ns – not significant; NT – no-tillage; CT – conventional tillage.

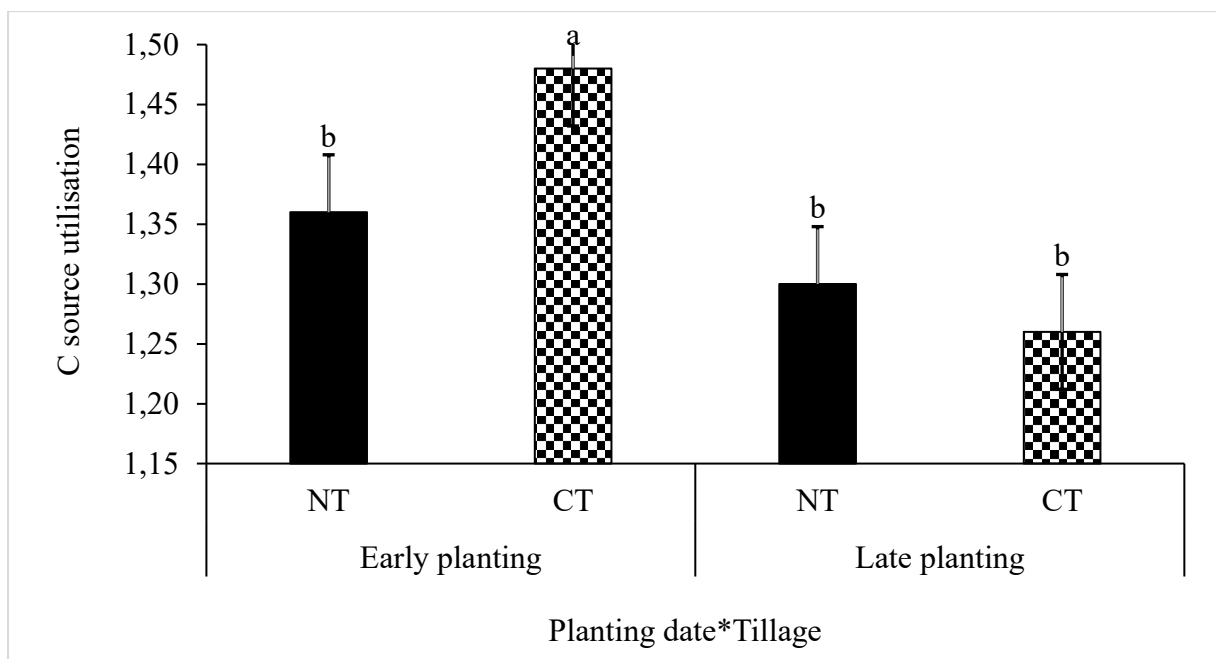


Figure 5.6: Interaction of planting date and tillage effects on the utilization of carbohydrates at the end of season three at Clau-Clau. Different letters (a and b) – significant differences ($p < 0.05$); NT – no-tillage; CT – Conventional tillage; Bars represent standard error.

5.5. Discussion

The greater activity of acid phosphomonoesterase and the utilisation of carbohydrates, carboxylic acids and polymers by soil microorganisms as C sources under late planting at Mphanama, could have been influenced by higher SOC (Chapter four) under late planting compared to early planting in the third growing season of the study. Extracellular phosphatases produce and release available P through the hydrolysis of organic P (Hegyi et al., 2021). According to Khurana et al. (2023), soil microbial functional diversity increases as SOM decomposition progresses. Thus, the lower SOC content (Chapter four) at early planting at Mphanama might have limited the activities of soil microbes since they rely on it for energy. The higher microbial richness and AWCD and the utilization of C sources by soil microorganisms observed under CT at Mphanama could be attributed to tillage creating favourable environmental conditions for soil microbial activities than under NT. In an undisturbed soil like NT, SOM is the main driver of soil enzymatic activities, therefore, the accumulation of SOC in arid and semi-arid regions takes longer than in cooler areas due to a lack of rainfall and the prevalence of high temperatures (De Varennes and Torres, 2011). The results can also be supported by the results of the PCA (Figure 5.1A and B) which showed a

strong positive associated between the soil microbial community diversity indexes and the utilisation of C sources under CT.

The observed significant higher soil microbial community or activity under CT than NT systems at both study sites can also be explained by the repeated application of pesticides under NT system to manage weeds. Previous authors have indicated that the application of pesticides can negatively affect the microbial community in the soil, particularly when pesticides are repeatedly applied (Jezierska-Tys et al., 2021; Medo et al., 2021; Jeyaseelan et al., 2023). Pesticides negatively affect or kill soil microorganisms when it directly interacts with them by activating the applied chemical in the bacterial cells which results in reducing their growth, population and function (Huang et al., 2017; Jeyaseelan et al., 2023). Conventional tillage involves significant physical disruption of the soil structure, consequently, opens soil aggregates, leaving protected SOM exposed to soil microbial attack and improving aeration. This sudden influx of easily accessible substrate and oxygen can cause a temporary increase in soil microbial activities.

The observed higher utilisation of carbohydrates and carboxylic acids by soil microorganisms under NT at Clau-Clau could have resulted from the application of crop residues because soil microorganisms are the main drivers of SOM decomposition and transformation. The results found by Zhong et al. (2023) also demonstrated a significant increase in soil microbial community indices specifically Shannon and Simpson under NT than CT. The lack of significant effects on soil enzymatic activities at both Mphanama and Clau-Clau align with the results observed by Acosta-Martinez et al. (2011), who found that tillage treatments (CT vs NT) did not affect B-glucosidase and phosphatase after 5 years of the investigation in a sandy loam soil under dryland cropping (semi-arid). The findings from this study showed that crop residue inputs under NT plots could not outperform CT in the given 3-year study period in this type of sandy soils, possibly because of crop growth stress due to extreme drought and high temperatures experienced at the site, resulting in poor biomass accumulation. For instance, tillage (CT vs NT) did not significantly affect the dry matter yield in this study, which further demonstrate that NT could not outperform CT on some of the measured soil properties.

Furthermore, the application of crop residues to NT treatment plots might have increased soil compaction in this type of soils, which might have decreased required oxygen by microbes within the soil particularly to those microorganisms requiring aerobic environments,

consequently, limiting soil enzymatic activities (USDA NRCS, 2010). According to the data gathered by Li et al. (2020), NT practice increased soil compaction and penetration resistance in a short-term (<6 years) and medium-term (6 – 12 years) duration, likely because the soil porosity rebounds after time, building a native structure with the difference in soil bulk density compared to CT. Another reason includes the accumulation of the crop residues or OM content on the soil surface promotes soil compaction due to the weight added on the soil surface over time (Luo et al., 2010). However, these results contradict with most previous studies (Mina et al., 2008; Pandey et al., 2014) who found greater soil enzymatic activities under NT in sandy soils with low SOC content within 3 years. The nature of soils might have led to such different observations because the soils used in this study have very low clay content and SOM as well as poor water holding capacity, which might have influenced enzymatic activities (USDA NRCS, 2010). Soils rich in clay have the ability to store SOM which increases or promote soil microbial communities (USDA NRCS, 2010).

The observed site-specific variations in the effects of planting date and tillage on the enzymatic activities and soil microbial community functional diversity could be influenced by the differences in types of soil, climatic conditions and associated agronomic activities. For instance, under semi-arid climate, microbial functional diversities were increased by CT and late planting which were consisted between season two and three, while under sub-humid climate, there effects of planting dates and tillage on soil microbial community functional diversity were not consistent. Under sub-humid climate, soil microbial community functional diversity was positively associated to NT and early planting during season two, while positively associated to CT and late planting during season three. These observations could be possible influenced by the climatic conditions which influences agronomic activities which are linked to soil functioning.

5.6. Conclusion

The results of this study demonstrate that late planting with lower rainfall distribution improved the activity of acid phosphomonoesterase at Mphanama. Conventional tillage is more beneficial for the utilisation of C sources by soil microorganism over time at Mphanama, while both NT and CT are important for the utilisation of C sources depending on a specific time of planting at Clau-Clau. The adoption of NT with crop residue inputs significantly enhanced

carbohydrates and carboxylic acids in sandy soils after 2 years at Clau-Clau. This study also demonstrated that tillage alone could not significantly affect carbohydrates but could improve carbohydrates when combined with planting time at Clau-Clau. Moreover, planting date alone has the potential to enhance soil functional diversity with late planting significantly improving utilization of carbohydrates, carboxylic acids and polymers in year 3 of the study in semi-arid environment at Mphanama. Most of these results especially the effects of tillage on soil functional diversity, contradict with the previous studies done on similar soil parameters which highlighted that the effects of CA system are site-specific. Thus, this study should be continued (>3 years) to further investigate the trend of NT on the soil microbiological community properties at both sites, since the study prioritised the adoption of NT to improve the quality of this type of soil. The results will offer insight knowledge of the effects of CA practices on soil C sources in the development of improving agricultural planning and decision making in similar environments.

6.0. GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1. General discussion

Smallholder farmers in Sub-Saharan Africa rely deeply on agriculture, growing mostly cereal crops including maize and sorghum for household purposes (Sithole et al., 2016). However, agricultural productivity and sustainability become more challenging under highly fragile and poor fertility soils, with inadequate soil water holding capacity and adverse climatic conditions (da Silva et al., 2020). To mitigate these challenges on crop production and soil quality enhancement, conservation agriculture (CA) was recognized to have the potential to protect soils, improve soil quality and conserve soil water through surface residue retention, reduced soil disturbance as well as crop rotation (Malobane et al., 2018). Thus, understanding the relationship between CA practices and soil functioning may likely improve soil management strategies and improve agricultural sustainability. The production of sorghum biomass may positively influence the recycling of soil nutrients such as the enhancement of SOC while improving the soil water status through crop residue retention, because soil cover reduces evaporation. This current study evaluated the effects of short-term (3 years) tillage managements system under arid and sub-humid climatic conditions in South African sandy soils. Furthermore, the time of planting, which consisted of early planting (December) and late planting (January) was investigated to further the understanding of the climatic impacts on sorghum crop production. Sorghum cultivars namely: Pan8816 and Macia were also evaluated to inform the selection of a suitable sorghum crop under the arid and subtropical climate in South Africa. Overall, this Chapter summarizes the findings presented in Chapters 3, 4 and 5 providing a holistic understanding of the impacts of the time of planting, tillage practices, crop rotation and sorghum cultivars on sorghum growth, yield and soil properties in sandy soils under semi-arid and sub-humid climatic conditions. This present study focused on the impacts of planting date and tillage as the main common factors throughout the thesis. Therefore, most of the general discussion covered these main factors.

6.2. Sorghum growth and yield

In this study, Chapter 3 investigated the effects of planting date (early vs late), tillage (NT vs CT), crop rotation (sorghum monoculture and sorghum cowpea rotation) and sorghum cultivar (Pan8816 and Macia) on sorghum growth, yield and soil water content. Higher sorghum crop yield during second growing season is aligned with taller plants and greater dry matter yield when sorghum was planted earlier than late at Clau-Clau. This relationship is not surprising because taller plants and higher dry matter yield demonstrate good crop growth which normally leads to higher grain yield. However, the soil water content did not directly drives these improvements, instead the observed taller plants and dry matter yield can be attributed to improved nutrient cycling under NT. The higher available P and K under NT with crop residue retention in the second growing season was consistent with the results of SOC suggesting that SOC improved the recycling of soil nutrients. For instance, soil microorganisms utilize SOC as substrate and break down crop SOM providing energy, and subsequently releases nutrients including N, P and K in to the soil (Thotakuri et al., 2024). The observed results aligned with the results reported by Chaudhary et al. (2019) who found higher concentration of N, P and K on NT compared to CT treatment. These results might be influenced by the retention of crop residues after each seasonal harvest (Ge et al., 2012b).

At Mphanama, the taller plants and greater TSW observed under early planting could be attributed to higher soil water content during the third growing season. Adequate soil water helps crops to access essential nutrients for growth and root development (Johnson, 2023). While the higher yield under the interaction of early planting and NT could be positively linked to the higher soil water content under the NT treatment in this study at Mphanama. However, the taller plants and TSW could not be explained by the direct effect of SOC, because higher SOC was observed under late planting than early planting. Mphanama had received very low rainfall from January during the third growing season in the year 2022/23 where late planting occurred which could have minimized the eluviation and mineralisation of SOC.

The improvement of crop growth and yield at Clau-Clau could also be explained by early planting when interacted with NT, which significantly increased the soil protein. The soil protein is responsible for promoting long-term SOC sequestration by creating a hydrophobic layer around soil aggregates (Son et al., 2024). However, all measured soil enzymatic activities had no significant relationship with SOC and crop growth or yield during season two and three

of the study at Clau-Clau. The higher TSW in NT could be influenced by the higher total N, and SOC observed under NT during season three at Clau-Clau. While the effects on yields at Clau-Clau could be explained by the enhancement of total SOC and the labile SOC fractions (coarse and fine POC), that at Mphanama was more related to soil water content. Early planting is beneficial in both semi-arid and sub-hum environments under NT, suggesting that farmers can practice the combination of early planting and NT in either one or the climatic conditions.

6.3. Soil water content

At Mphanama, no-tillage with the addition of crop residues likely improved soil water content levels by improving water infiltration and minimizing water runoff and evaporation (Jin et al., 2020). In this study, crop residues were retained under NT plots after each harvest, which might have played a role in improving soil water content possibly by reducing evaporation and minimizing surface water runoff which might have promoted water infiltration (Jin et al., 2020). The improvement of soil water content in the NT plots with crop residue maintenance under sandy soils has been observed in previous studies, which agree with the results observed at Mphanama in this study (Murphy, 2015; Serme et al., 2015; Ayman, 2023). The observed higher soil water content under NT at Mphanama coincided with taller plants, higher grain yield and TSW (Chapter three: Table 3.3), suggesting that the higher soil water content could have increased these parameters during growth stage development. However, the higher soil water content observed at Mphanama was not directly related to changes in SOC from tillage or rotation as main factors but can be explained by the early planting time. Sorghum plants were significantly taller when planted early which might have contributed to a greater accumulation of crop residue retention in plots under NT. This enhanced residue cover could have further reduced evaporation and reduced water runoff, thus improving soil water content. Moreover, since NT did not significantly improve SOC at Mphanama, the relationships between soil water content and other measured soil properties including enzymatic activities, and soil microbial functional diversity except the microbial evenness (E), soil protein and POC fractions were not directly evident. Soil properties such as SOC are generally known to promote soil aggregate stability, resulting in improved water infiltration rate into the soil, which in turn improves soil water content (Murphy, 2015). The primary driver of improved soil water in soils at Mphanama was the physical presence and associated effects of crop residues, especially when combined with early planting.

On the other hand, this study demonstrated that the higher soil water content at Clau-Clau was observed under CT rather than NT. This observation cannot be exclusively explained by the improvement of SOC, their fractions and total N as these were higher under NT. Similarly higher soil water content under CT was not directly related to GRSP and the soil microbial functional diversity, with the exception of amino acid utilisation which was also higher under CT. The higher soil water content at Clau-Clau can be explained by the slightly higher plant height and dry matter yield under CT during season three. Higher crop biomass production under CT might have provided better ground cover and shade, while minimizing evaporation compared to the NT plots. Additionally, the higher rainfall received at Clau-Clau likely reduced the overall sensitivity of soil water to the different treatments compared to Mphanama. Moreover, the higher soil water content under CT at Clau-Clau could be caused by other soil physical properties influenced by ploughing like water infiltration rate, soil porosity as well as reduced bulk density. According to Villamil et al. (2015), soil compaction is higher under NT than CT. Ploughing reduces compaction and surface capping, making the surface rough, which is likely to promote soil pores for better water infiltration. These findings are consistent with those from Acharya et al. (2019), who reported higher soil water content under CT than NT treatments within 0 – 30 soil depth in soil dominated by fine sandy loam texture. Acharya et al. (2019) suggested that lower bulk density under CT (1.41 g cm^{-3}) than NT (1.52 g cm^{-3}) in the topsoil (15 cm depth) could influence this result. Another previous research reported a significantly lower soil water content under NT than CT which was attributed to CT modifying the soil surface (Obalum et al., 2011).

6.4 Soil properties

At Mphanama, the observed higher SOC with late planting (Chapter 4: Table 4.5) could explain the higher utilization of SOC by the soil microbial community. This is further supported by the significantly higher microbial richness (R), AWCD indices, carbohydrates, carboxylic acids and polymers which were also significantly higher under late planting at the end of season three. These results are consistent with existing literature. For instance, Weng et al. (2021) highlighted the positive role that carbohydrates play as C sources for soil microbes leading to higher AWCD, which is consistent with the results obtained at the end of season three at Mphanama. Furthermore, the observed results align with results observed by Zhu et al. (2012)

who found positive correlations between SOC and Shannon indexes of fungi. Their study reported that the improvement of SOC improved soil fungal phylogenetic diversity. These results are supported by other previous studies, which have demonstrated that soil microbial community diversity is often linked to the mineralization of organic materials within the topsoil layer (Kubartova et al., 2009; Zhang et al., 2020; Mi et al., 2021). Moreover, higher soil microbial community functional diversity under late planting at Mphanama could be associated with the improvement of soil nutrients (Ca and Mg) which were also significantly higher under these conditions. Similarly, Zhu et al. (2012), found a positive correlation between Shannon index of fungi and soil nutrients, particularly total N. The positive relationship between soil nutrients and soil microbial community functional diversity was previously demonstrated by others (Xiao et al., 2019; Chen et al., 2020; Pratibha et al., 2023). However, total N, available P and K as well as soil pH could not be directly related to the observed higher soil microbial functional diversity at Mphanama.

The higher SOC observed under late planting at Mphanama could potentially be influenced by less intense rainfall which might have minimized the possibility of soil erosion and nutrient leaching. Furthermore, the higher SOC, especially the fine POC fractions and soil microbial community functional diversity under late planting, indicates that these labile fractions of SOC could have positively influenced the diversity and the activities of acid phosphomonoesterase as a labile substrate under late planting at the end of season three at Mphanama. However, these positive effects of late planting, including higher SOC, soil microbial functional diversity, fine POC, activities of acid phosphomonoesterase, and increased Ca and Mg levels under late planting, did not correlate with the observed higher plant height and TSW that occurred under early planting at Mphanama, suggesting that the observed higher plant height and TSW could rather be attributed to the early rainfall received and higher soil water content during the early planting. Tillage did not have significant effects at Mphanama and this could be a consequence of crop growth and development failure during the second growing season of the study due to extreme drought. Such crop production failures due to extreme drought is not uncommon in semi-arid climates, as similarly reported by Acharya et al. (2024), who also found that severe drought negatively affected crop production in a study on the effects of cover crops on SOC storage under maize-sorghum rotation. The reduction in crop biomass production negatively influences the accumulation of SOC and this might be more pronounced in sandy soils because of their poor soil aggregate stability, nutrient holding capacity and higher drainage rates.

The higher soil microbial community functional diversity observed under CT at Mphanama might be attributed to the relatively recent transition of NT adoption from CT cropping system. For instance, Acharya et al. (2024), also observed a decline in soil POC and SOC in the year that soil cover cropping was introduced. Similarly, Mbuthia et al. (2015), noted that the convention of CT to NT systems may influence the dynamics of SOC which may result in different or inconsistent results in a long-term of NT adoption.

At Clau-Clau, the increased SOC under NT during the second and third growing seasons could be associated with the improvement in the content of POC and MAOC fractions. This increased content of POC and MAOC fractions at Clau-Clau could be explained by the decomposition of crop residues retained on the soil surface which might have contributed to the accumulation of SOC under NT. Acharya et al. (2024) also observed positive effects of cover crops on SOC storage under a maize and sorghum rotation system in a semi-arid zone. However, their study was conducted under irrigated cropping systems on clayey loam soil which present different conditions compared to this study. Despite these differences, the findings of this research support the broader understanding that the maintenance of crop residues improves soil POC and MAOC fractions and SOC over the short-term (3 years).

Furthermore, the observed higher SOC under NT treatment at Clau-Clau could be explained by the measured higher carbohydrates and carboxylic acids under the same conditions during season two. Carbohydrates play a huge role in recycling and regulating SOC content during the degradation of SOM (Zhao et al., 2020). The results of this study are consistent with the results reported by Weng et al. (2021) who demonstrated that SOC strongly affected soil microbial functional diversity. However, despite the improvement of SOC, its accumulation did not influence soil pH either. Generally, crop residue retention increases soil pH by increasing base cations in the surface layers after the decomposition of crop residues (Chen et al 2020, Acharya et al., 2024).

6.5. Major findings

Planting date was one of the major contributing factors. Early planting significantly improved sorghum growth parameters irrespective of the growing seasons and study sites. In contrast, late planting, despite its negative impact on crop growth was a key contributor to improving

soil properties including chemical properties, soil water content, SOC, soil enzymatic activities and the utilisation of C sources regardless of the growing seasons under semi-arid climatic condition. Tillage practices also played a crucial role. NT significantly improved most sorghum growth parameters, soil chemical properties, SOC and their fractions, while CT practice contributed mostly to the improvement of soil water content and community functional diversity under sub-humid climatic condition irrespective of the growing seasons. Under semi-arid climatic condition, CT also played an important role on increasing the utilisation of C sources. However, both NT and CT had 50% chances of improving selected soil chemical properties under semi-arid climate, irrespective of the growing seasons. Interactions among management practices were particularly important. Early planting combined with either tillage practice (NT or CT) or crop rotation (S-C-S or S-S-S) improved sorghum growth parameters and selected soil properties across studied climatic conditions. The interaction between late planting and both tillage practices (NT vs CT) and crop rotation (S-S-S) significantly increased soil water content across selected study sites. The S-S-S rotation was the main crop rotation which improved soil chemical properties and water content when interacted with either planting date (early planting or late) and tillage (NT and CT) regardless of the study sites.

6.6. Conclusion

The results of this three-year study indicate that the effects of planting date, tillage, crop rotation and sorghum cultivars are highly site specific, and are particularly influenced by contrasting climatic conditions. At Mphanama, early planting increased plant height and TSW under semi-arid climate. Sorghum grain yield was increased when early planting interacted with NT. At Clau-Clau, early planting increased plant height, dry matter yield, grain yield and TSW under a sub-humid climate. Pan8816 crops were taller when planted late under NT, while Macia crops were taller when planted late under CT at Clau-Clau. The adoption of NT with crop residue retention improved SOC, POC fractions (coarse, fine and mineral), TSW, available P, K and total N in a sandy soil under sub-humid climatic condition at Clau-Clau. Late planting improved SOC, fine POC carbon fraction, Ca and Mg at Mphanama. At Clau-Clau, CT significantly increased soil water content while NT with crop residues enhanced soil water content at Mphanama. The combination of early planting $\times$ NT and late planting $\times$ CT enhanced the soil protein at Clau-Clau. At Mphanama, late planting increased the activities of acid phosphomonoesterase, AWCD, carbohydrates, carboxylic acids and polymers. More at

Mphanama, CT treatment increased microbial richness (R), and AWCD indices and almost all measured soil functional diversity. While NT increased soil microbial evenness (E) under a semi-arid climate, late planting was also noticed with improving AWCD, carbohydrate and carboxylic acids at Clau-Clau. The interaction of late planting $\times$ NT and the interaction of early planting $\times$ CT increased carbohydrates at Clau-Clau.

These findings imply that the benefits of NT relative to CT, and early planting relative to late planting, sorghum yields, soil water content, other soil chemical properties, SOC and its fractions as well as soil microbial activity on sandy soils under dryland production conditions, depend on site-specific characteristics, especially rainfall received. Therefore, successful adoption of CA requires tailored management strategies that consider local agro-climatic conditions.

6.7. Recommendations

- i. Implementing NT with crop residue retention as a sustainable practice for improving SOC, nutrient availability, and grain yield in sandy soils under sub-humid climates should be prioritized.
- ii. The early planting of sorghum crop should be prioritized in regions with low rainfall and poor distribution to increase biomass production.
- iii. A long-term (>3 years) study should be conducted to further investigate the impacts of NT with crop residues on SOC at Mphanama and soil water content at Clau-Clau in these types of sandy soils, especially considering that the soil characteristics were improved with an increase in the number of seasons.
- iv. Inputs of organic amendments such as manure and compost should be prioritized for improving soil MBC, GRSP and enzymatic activities at both study sites over the short-term.
- v. Crop rotation with other drought resistant legume crops, such as pigeon-pea, may be required to increase chances of biomass production, which may improve soil quality in the study areas.

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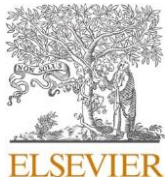
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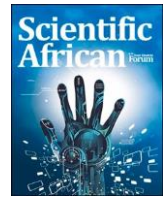
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Short-term tillage management effects on grain sorghum growth, yield and selected properties of sandy soil in a sub-tropical climate, South Africa

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ABSTRACT

Poor soil fertility and water holding capacity, coupled with climate change, threaten smallholder agriculture under dryland conditions, particularly in sandy soils. The resilience of sorghum makes it an ideal candidate crop for conservation agriculture (CA), under these conditions, but its productivity and effectiveness could depend on the cultivar used, planting time, tillage, and rotation. This study determined the effects of these factors on selected soil properties, growth and grain yield of two sorghum cultivars in sandy soils, under semi-arid conditions. The trial was conducted between 2019 and 2022 on a sandy soil with <10 % clay and <1.0 % carbon, at Clau-Clau village in Mpumalanga province, South Africa. The experiment had a randomized complete block design (RCBD) set up, in a strip-split-split-plot treatment structure with three replications. The treatment factors were tillage (conventional tillage (CT) and no-till (NT)), planting date (early and late), and rotation (with cowpea or sorghum monoculture) and sorghum cultivar (Pan 8816 and Macia). In the second growing season, early planted sorghum outperformed the late planted crop, with 44.4 % greater height and 36.1 % higher 1000-seed weight. Furthermore, the grain yield (1.33 and 0.56 t/ha, respectively) and dry matter yield (2.38 and 1.10 t/ha, respectively) were significantly higher for early than late planting in season 2. The NT treatment had significantly higher SOC, available P and exchangeable K than CT treatment in season 2. In season 3, early planting had 30.4 % higher exchangeable K than late planting, while NT increased total N and SOC by 50 and 34.8 %, respectively than CT. The findings of this study show the positive effects of early planting and NT on sorghum grain and dry matter yields, while effects on soil properties were greater during the season with higher rainfall, with no effects of cultivar and rotation on this infertile sandy soil.

Abbreviations: ANOVA, analysis of variance; ARC, Agricultural Research Council; Ca, calcium; CA, conservation agriculture; CEC, cation exchange capacity; CT, conventional tillage; DALRRD, Department of Agriculture, Land Reform and Rural Development; EC, electrical conductivity; K, potassium; LAN, Limestone Ammonium Nitrate; MAP, Monoammonium Phosphate; Max, maximum; Min, minimum; Mg, magnesium; mg/kg, milligram per kg; NT, no tillage; P, phosphorus; PD1, early planting date; PD2, late planting date; R1, first rotation; R2, second rotation; RCBD, randomized complete block design; S-C-S, sorghum-cowpea-sorghum; SOC, soil organic carbon; S-S-S, sorghum-sorghum-sorghum; TN, total nitrogen; t/ha, tonnes per hectare; V1, Pan8816; V2, Macia.

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Introduction

The sustainability of crop production in Africa is threatened by multiple challenges such as low soil fertility, poor management strategies, and extreme weather events, due to climate change [1–3]. Increasing demand for food, feed, fibre and energy production, has led to the expansion of cultivation onto marginal land, including sandy soils. These soils are characterised by low soil organic carbon content (SOC), limited cation exchange capacity (CEC), and poor moisture retention (Huang and Hartemink, 2020). The low fertility and poor water-holding capacity of sandy soils limit crop productivity. Climate change amplifies these challenges, posing severe threat to sustainable crop production for many smallholder farmers in Africa, who continue to attain low yields. Prolonged droughts associated with climate change intensify water scarcity, significantly affecting crop production. Additionally, extreme weather events, including unexpected storms, accelerate nutrient depletion from agricultural soils through runoff and erosion, thus exacerbating soil fertility decline.

Conventional tillage (CT), which is commonly practised by smallholder farmers, enhances runoff and erosion, exacerbating nutrient losses particularly in sandy soils, consequently hampering crop production. Ekwue and Harrilal [4] reported that sandy soil experienced 87.6 % greater soil loss compared to clay loam soils resulting in reduced crop yields. This soil degradation, coupled with the impacts of climate change, poses significant challenges to agricultural productivity in Sub-Saharan Africa (SSA). Projections suggest a 3.2 % decline in cereal crop production by 2050 due to climate change [5]. However, the adoption of climate-resilient agricultural practices that can improve soil quality, water availability, mitigate erosion and improve organic matter can contribute to the sustainability of crop production in regions with sandy soils [6,7].

Conservation agriculture has a potential to enhance soil quality on sandy soils in marginal areas. By reducing soil disturbance, retaining crop residues as mulch and crop rotation, CA enhances soil nutrient cycling [8,9], improves soil moisture storage and minimises greenhouse gas emission [2]. The retention of crop residues improves the SOC concentration and enhances soil structure and nutrient cycling. However, this effect depends on the quality of the crop residues (C/N, lignin, polyphenols etc.), which governs the rate of decomposition [2]. The rotation of cereals with legume crops, such as cowpea, could enhance soil fertility status through biological nitrogen fixation. However, even greater benefits can be obtained by coupling CA with drought-tolerant cereal crops such as sorghum that offer stable yields in arid and semi-arid climates.

Sorghum has received renewed interest from researchers due to its ability to withstand drought and other extreme climatic conditions [1,2,10]. Sorghum is the fifth most important cereal crop in the world after rice, wheat, corn/maize and barley, and is mostly cultivated for grain for human and animal consumption and bioenergy production in arid and semi-arid tropical regions including Africa [11]. Sorghum can contribute to household food security and secure livelihoods in marginal areas of South Africa [1]. The leaves of this crop are well protected by a waxy cuticle and roll-up to minimize transpiration during drought periods, while the crop becomes dormant when drought continues [11]. While several researchers have worked on sweet sorghum [2,10,12], there is limited knowledge about the performance of grain sorghum under CA in South Africa, especially on sandy soils under smallholder agriculture.

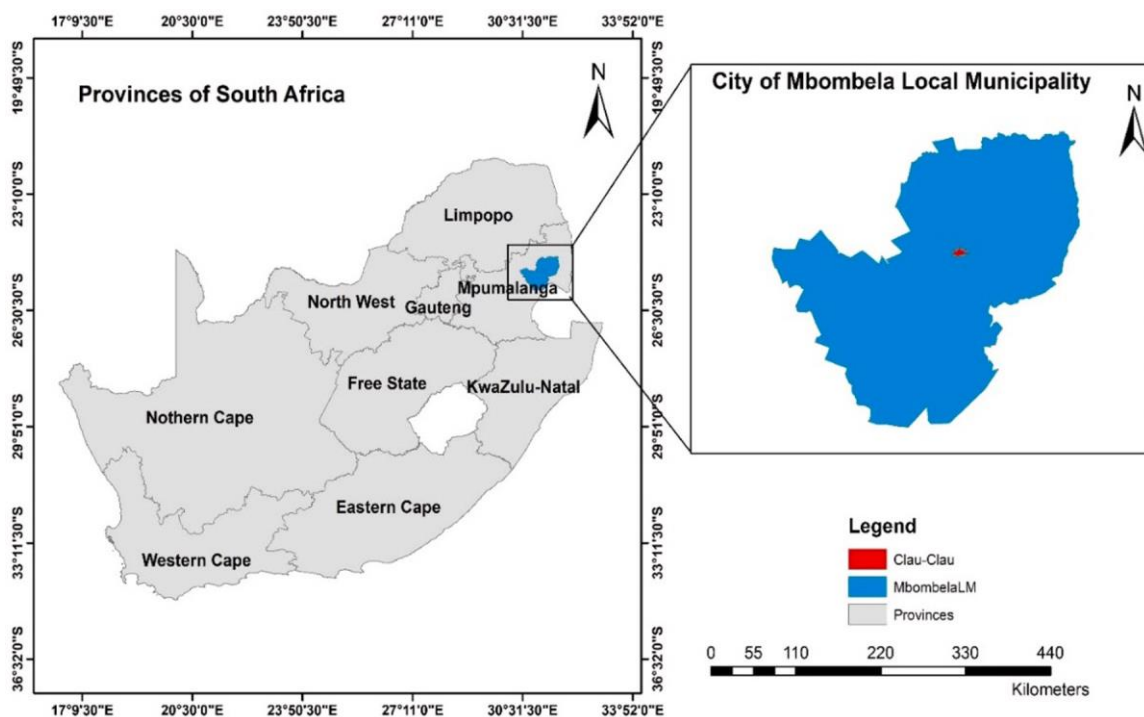


Fig. 1. The South African map showing the selected site as reported by the local municipalities.

Malobane et al. [13], showed that the adoption of CA can increase sorghum yields in drought-prone areas of South Africa. This therefore highlights the potential of sorghum for smallholder farmers who are largely located in dry areas. However, yield could depend on both the cultivar and cropping systems. Therefore, identifying suitable cropping systems that will foster resilience to climate change and improve the quality of sandy soils particularly in arid and semi-arid areas of South Africa, is crucial. Conservation agri- cultural practices and knowledge of appropriate sorghum cultivars, planting date and rotation could contribute to this goal.

The implementation of CA has the potential to improve soil structure, enhance nutrient availability, and increase moisture retention, leading to enhanced soil health and increased productivity particularly in poor soils, such as sandy soils. However, some studies have reported conflicting findings on the effects of CA on sandy soils [14]; (Mchunu et al., 2011); [15]. For example, da Silva et al. [15] observed a 6 % yield increase soyabean yields under NT compared to CT on sandy soils. In contrast, Lasisi and Aluko [14] reported a higher yield on CT than NT plots on similar soil types. These conflicting findings necessitates more research to elucidate the effects of CA on the performance of different sorghum cultivars on sandy soils on contrasting sites. This study investigated the effects of planting date, tillage, and crop rotation on the growth, dry matter, yield of two sorghum cultivars, and selected soil properties on sandy soil under sub-tropical climatic conditions. By studying these factors, this study aims to provide valuable insights into the adaptability and performance of different sorghum cultivars and CA practices. Overall, this study is important for smallholder farmers in regions with sandy soils, as it aims to provide evidence-based recommendations for improving crop yields, enhancing soil health, and building resilience to climate change. By identifying the most effective combination of CA practices, sorghum cultivars, and planting dates, farmers can optimize their agricultural production and enhance soil health and build resilience to climate change.

Materials and methods

Site description

The study was conducted at Clau-Clau village in Mpumalanga province, South Africa (Fig. 1). Clau-Clau village is situated within the Mbombela Local Municipality in Mpumalanga Province of South Africa. The area has a sub-tropical climate and receives a mean annual rainfall of approximately 748 mm, which occurs between November and February [16]. The mean minimum and maximum temperatures range from -2.0°C and 41.7°C , respectively [17]. The area is characterised by predominantly sandy soils with $<10\%$ clay [16]. The soil at Clau-Clau had grey to grey-brown sandy topsoil over yellowish brown sandy subsoil, classified as Fernwood which is equivalent to Hyperdystric Stagnic Regosols [18]. Prior to the study, the standard practice in the area was conventional tillage using a mouldboard plough, with maize being grown annually. Temperature and rainfall conditions are shown in Figs. 2 and 3, respectively. The rainfall was above average between October and March, except November and December in the 2020–2021 season and February in the 2021–2022 season (Fig. 3).

Experimental design

The experiment was carried out in randomized complete block design with a strip-split-split-plot treatment structure, replicated three times [19]. Planting date (early and late) and tillage system were assigned to the horizontal and vertically arranged main strips, respectively (Fig. 4). Early planting was done in the first week of December, whilst late planting was done in the second week of January in every growing season. The two tillage systems were conventional tillage (CT) with crop residue removal and no-till (NT) with crop residue retention. This vertical-horizontal split plots gave intersection plots, which were split into two and assigned to the two crop rotations i.e. sorghum-sorghum-sorghum (S-S-S) and sorghum-cowpea-sorghum (S-C-S). The rotations were divided in two to accommodate the two selected cultivars i.e. Pan 8816 and Macia. These cultivars are known to have the ability to tolerate dry weather condition and are characterized by low tannin and are semi-dwarf hybrids. The experiment consisted of 16 treatments with three replicates, which resulted in 48 experimental plots, of $6 \times 4.5\text{ m}$ size. The experiment was conducted across three growing seasons,

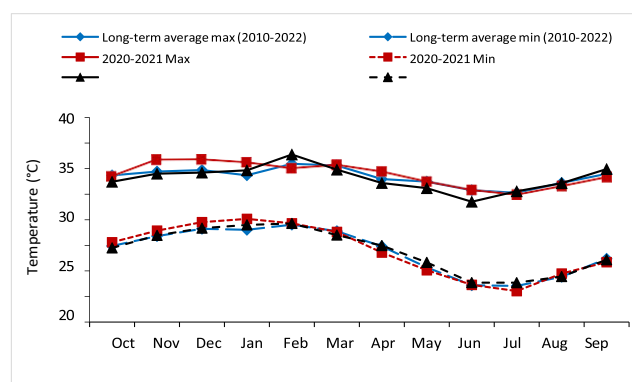


Fig. 2. Long-term (2010 – 2022) and seasonal (2020 – 2021 and 2021 – 2022) temperature conditions.

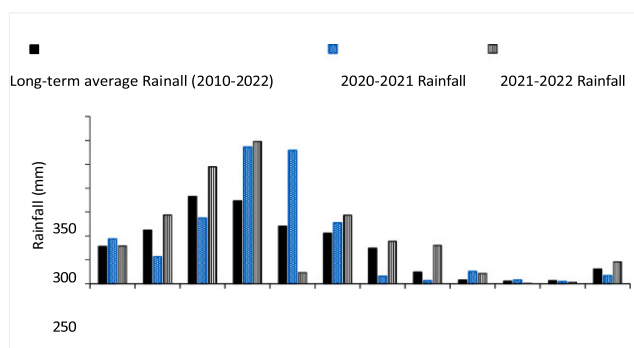


Fig. 3. Long-term (2010 – 2022) and seasonal (2020 – 2021 and 2021 – 2022) rainfall conditions.

between 2019/20 – 2021/22.

The management of non-experimental variables

The whole experimental field was ploughed with a mouldboard plough and harrowed to breakdown large clods to make a fine tilth at the onset of the experiment in 2019, marking the first growing season. Residue retention was only applied on the NT plots after each harvest whereas the CT plots were left bare throughout the experimental period. The CT plots were ploughed to a depth of approximately 30 cm at the beginning of each growing season using a mouldboard plough and harrowed. During the second growing season (2020/2021), cowpea was planted in some plots, followed by sorghum in the third season (2021/2022) as part of a crop rotation strategy. The conventional tillage plots were ploughed using a mouldboard plough and harrowed. In both CT and NT plots, hand hoes were used to open rows for planting. To ensure optimal nutrient levels, fertilizer was applied based on the initial soil analysis. Monoammonium Phosphate (MAP) fertilizer (218 kg/ha) was applied at planting to supply N (24 kg/ha) and P (48 kg/ha) while Limestone Ammonium Nitrate (LAN) fertilizer (259 kg/ha) was applied as top-dressing after six weeks of planting to supply an additional 72.5 kg N/ha. Glyphosate (N-(phosphono-methyl) glycine, 360 g/L) was used to kill the weeds in all plots after harvest and before the next growing season. Cylam 50 EC (Lambda-cyhalothrin (pyrethroid), 50 g/L) was used to control pests in the grain sorghum crops. Sorghomil Gold (600 SC) was used to control weeds in all the NT plots whereas hand hoes were used to remove weeds in the CT plots.

Soil sampling and analysis

Three soil samples were collected randomly before and after each harvest using an auger at 0 – 20 cm depth in each experimental plot, and were mixed to make a composite sample, making a total of 48 samples from the 48 plots. The samples were air-dried and sieved (<2 mm) before analysis. Soil pH and electrical conductivity (EC) were measured at 1:2.5 soil: water ratio (Okalebo et al. 2012). Soil organic carbon (SOC) was determined following the Walkely-Black method [20]. Soil particle size distribution was determined following the hydrometer method after dispersion with 1 M sodium hexametaphosphate [21]. Total N (TN) was determined following the dry combustion method using the Flash 2000 organic Elemental Analyzer (Milan, Italy). Soil available P was determined following the P-Bray 1 method [22]. Exchangeable Ca, K and Mg were determined by the ammonium acetate method [23]. The initial soil properties are presented in Table 1.

Sorghum growth and dry matter yield

Plant measurements included plant height, grain yield, 1000 seed mass and aboveground dry matter yield. Plant height was measured using a tape measure from the base to the tip of the plants at the harvest stage. Grain yield was harvested from a net plot measuring 2.5 m × 4 m. The harvested grain was then threshed, weighed and expressed as t/ha. To determine the average weight of individual seeds, a representative sample of 1 000 seeds was weighed. This weight was reported as 1000-seed weight in grams. The above ground dry matter was also harvested from the net plot and dried in an oven at 60 °C for 24 h, weighed and expressed as t/ha. The results section of this study presents data from the second (2020–2021) and third (2021–2022) growing seasons after the treatments were implemented. In season 1, the whole experimental field was ploughed before the treatments were implemented and the crop residues produced from season 1 were used to cover the soil under no-tillage.

Statistical analysis

Analysis of variance (ANOVA) was performed using JMP 16 statistical package software (SAS Institute, Inc., Cary, NC, USA, [24] to assess the effects of tillage, planting date, cultivar and rotation on the soil and yield parameters of sorghum. Mean separations were performed using Duncan's Multiple Range Test at a significance level of $p < 0.05$.

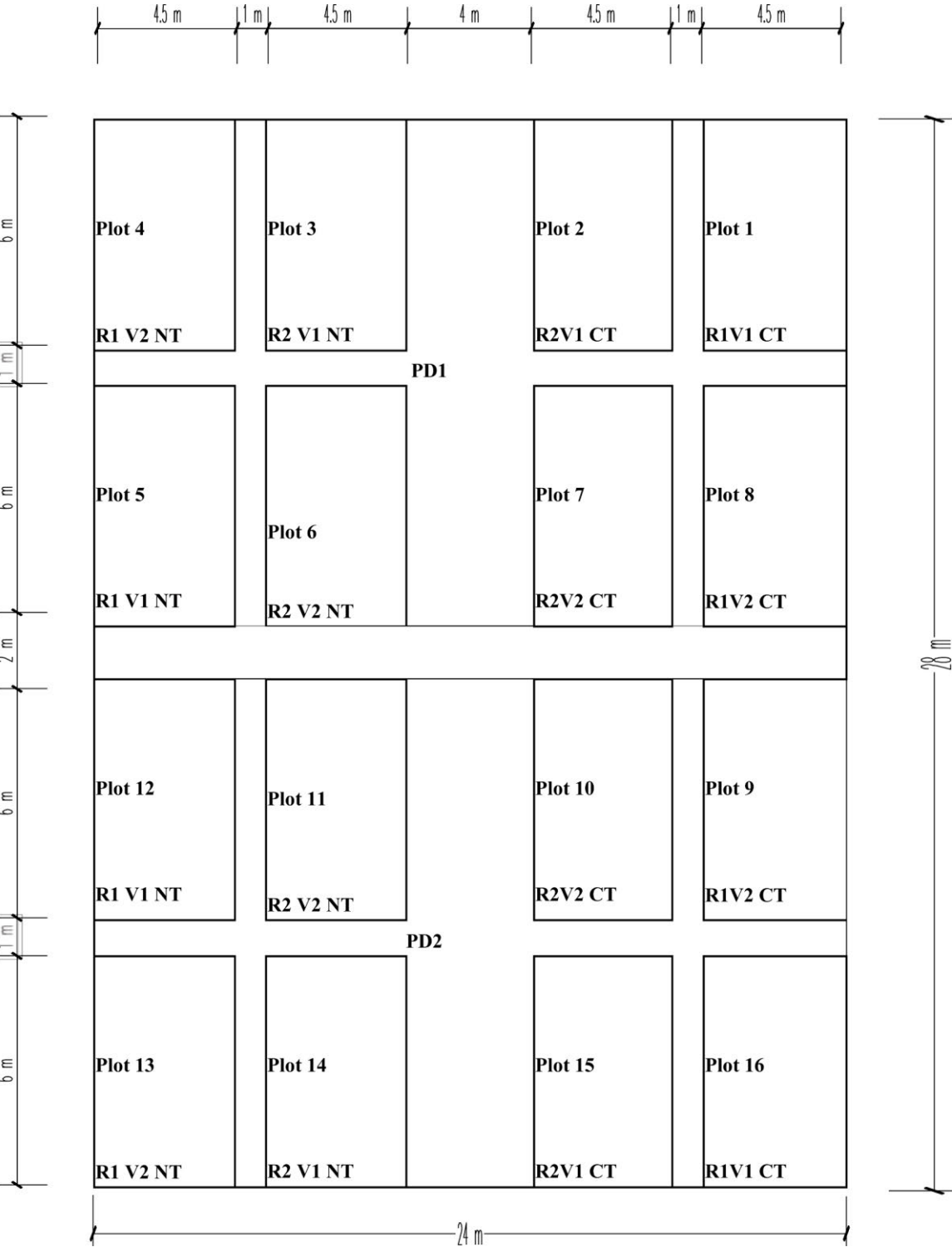


Fig. 4. The field experimental design map. PD1 and PD2 – early planting date and late planting date, respectively; NT and CT – No-Till and conventional tillage, respectively; R1 and R2 – sorghum-cowpea-sorghum and sorghum-sorghum-sorghum, respectively; V1 and V2 – Pan8816 and Macia, respectively.

Table 1
Initial soil properties at Clau-Clau village.

Parameters	Clau-Clau
pH (H ₂ O)	5.57
EC (mS/m)	0.97
P (mg/kg)	7.6
K (mg/kg)	16
Ca (mg/kg)	57
Mg (mg/kg)	20
Total N (%)	0.05
SOC (%)	0.39
Sand (%)	88
Silt (%)	4
Clay (%)	8
Textural Class	Sand

Note: pH (H₂O) – pH measured in water; EC – electrical conductivity; P – available phosphorus; K – exchangeable potassium; Ca – exchangeable calcium; Mg – exchangeable magnesium; N – total nitrogen; SOC – soil organic carbon;; mS/m – millisiemens per meter; mg/kg – milligram per kg; % – percent.

Results

Effects of planting date, tillage, and rotation on selected soil properties

The interactions between planting date, tillage and rotation had no significant effects on any of the measured soil properties. Additionally, planting date did not have significant effects on soil properties measured in the second season of the study. However, tillage significantly affected phosphorus (P), potassium and SOC in season 2 of the study. Phosphorus was significantly higher ($p < 0.05$) under NT (22.8 mg/kg) than CT (16.2 mg/kg) plots (Table 2). A significantly higher ($p < 0.05$) potassium (K) was also observed under NT than CT plots (43.8 to 36.0 mg/kg, respectively) (Table 2). Furthermore, SOC was significantly higher under NT compared to CT plots (0.53 and 0.39 %, respectively) (Table 2). Similar, to the second season, all the measured soil properties in season 3 were not significantly affected by the interactions of the planting date, tillage and rotation. In additions, rotation did not significantly affect any of the measured soil properties. However, significantly higher K was observed at early than late planting (49.31 and 37.79 mg/kg, respectively) (Table 3). Moreover, tillage significantly affected total nitrogen (N) and SOC, with NT having 50 % increased total N and 34.8 % higher SOC than CT plots in season 3 (Table 3).

Effects of planting date, tillage, cultivar and rotation on plant height

Early planting generally resulted in taller sorghum plants during the second season (Table 4). The magnitude of the difference was significantly influenced by interaction with planting date, tillage and cultivar. For instance, early planting × NT × Pan8816 had the highest average height (138 cm), whilst several other combinations with early planting including both cultivars and tillage practices also had significantly taller plants compared to late planting × NT × Macia (56.67 cm) and late planting × CT × Pan8816 (62 cm) (Fig. 5). Examples of this include early planting × NT × Macia (133 cm), early planting × CT × Pan8816 (133 cm) and early planting ×

Table 2
Selected soil properties in season 2 (2020–2021) as affected by planting date and tillage.

Treatment	Total N %	P (mg/kg)	K (mg/kg)	SOC %	Ca (mg/kg)	Mg (mg/kg)	pH (H ₂ O)
Planting date							
Early	0.05	18.9	40.1	0.47	157	42.9	5.20
Late	0.05	20.1	39.7	0.44	111	33.4	5.07
	ns	ns	ns	ns	ns	ns	ns
Tillage							
NT	0.06	22.8a	43.8a	0.53a	151	38.7	5.26
CT	0.05	16.2b	36.0b	0.39b	117	37.6	5.10
	ns	$p < 0.05$	$p < 0.05$	$p < 0.05$	ns	ns	ns

Note: Different letters (a and b) – significant differences ($p < 0.05$); ns – no significant; NT – no-till; CT – conventional tillage; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; SOC – soil organic carbon; Ca – exchangeable calcium; Mg – exchangeable magnesium; % – percent; mg/kg – milligram per kg.

Table 3
Selected soil properties in season 3 (2021–2022) as affected by planting date, tillage and rotation.

Treatment	Total N %	P (mg/kg)	K (mg/kg)	SOC %	Ca (mg/kg)	Mg (mg/kg)	pH (H ₂ O)
Planting date							
Early	0.06	26.1	49.3a	0.56	148	38.1	4.65
Late	0.05	31.1	37.8b	0.52	122	25.8	4.96
	ns	ns	$p < 0.05$	ns	ns	ns	ns
Tillage							
NT	0.06a	30.3	45.7	0.62a	139	29.1	4.90
CT	0.04b	26.8	41.5	0.46b	130	34.8	4.72
	$p < 0.05$	ns	ns	$p < 0.05$	ns	ns	ns
Rotation							
S-C-S	0.054	25.8	40.6	0.54	127	30.0	4.99
S-S-S	0.055	31.4	46.5	0.54	142	33.9	4.62
	ns	ns	ns	ns	ns	ns	ns

Note: Different letters (a and b) – significant differences ($p < 0.05$); ns – no significant; NT – no-till; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; pH (H₂O) – pH measured in water; N – total nitrogen; P – available phosphorus; K – exchangeable potassium; SOC – soil organic carbon; Ca – exchangeable calcium; Mg – exchangeable magnesium; % – percent; mg/kg – milligram per kg.

Table 4
The effects of planting date, tillage and cultivar on plant height, dry matter, yield and 1000 seed weight in the second growing season.

Second growing season (2020 – 2021)					
Treatment		Plant height (cm)	Dry matter (t/ha)	Yield (t/ha)	1000 seeds weight (g)
Planting date	Early	133 a	2.38 a	1.33 a	48.3 a
	Late	92.1 b	1.10 b	0.56 b	35.5 b
		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
Tillage	NT	115	1.96	0.88	43.3
	CT	110	1.51	1.00	37.5
		ns	ns	ns	ns
Cultivar	Pan8816	116	1.98	1.07	45.8
	Macia	108	1.49	0.82	35.0
		ns	ns	ns	ns

Note: Different letters (a and b) – significant differences ($p < 0.05$); ns – no significant; NT – no-till; CT – conventional tillage; cm – centimeters; t/ha – tonnes per hectare; g – gram.

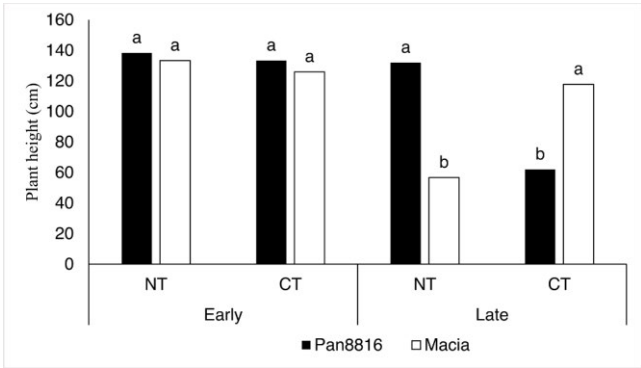


Fig. 5. The interaction effects of planting date, tillage and cultivar on plant height in the second growing season. Different letters (a and b) show significant differences ($p < 0.05$); NT: no-till; CT: conventional tillage.

CT × Macia (126 cm) (Fig. 5). For early planting, there was no differences in plant height between the two cultivars under either NT or CT (Fig. 5). However, under late planting and NT, Pan8816 plants were taller than Macia (Fig. 5). Conversely, the opposite was true under conventional tillage (CT) (Fig. 5). Early planting had significantly higher plant height than late planting in season 2 (133 and

92.1 cm, respectively) (Table 4). In season 3, planting date, tillage, cultivar, rotation and their interactions had no significant effects on sorghum plant height (Table 5).

Effects of planting date, tillage, cultivar and rotation on sorghum dry matter

Planting date, tillage, cultivar, rotation and their interactions had no significant effects on sorghum dry matter in the third growing season (Table 5). However, planting date significantly ($p < 0.05$) affected dry matter in the second growing season. Early planting resulted in a significant increase in sorghum dry matter weight compared to late planting. Dry matter weight was nearly double at early planting (2.38 t/ha) compared to late planting (1.10 t/ha) (Table 4).

Effects of planting date, tillage, cultivar and rotation on sorghum grain yield

In season 2, planting date significantly ($p < 0.05$) affected sorghum grain yield with higher grain yield observed at early planting than late planting (1.33 and 0.56 t/ha, respectively) (Table 4). Contrary to this, tillage and cultivar had no significant effects on sorghum grain yield in season 2. Planting date, tillage, cultivar, rotation and their interactions had no significant effects on sorghum grain yield in season 3 (Table 5).

Effects of planting date, tillage, cultivar and rotation on 1000 seeds weight

Tillage, cultivar and their interactions had no significant effects on 1000 seeds weight in season 2. However, 1000 seeds weight was 36.1 % significantly ($p < 0.05$) greater at early planting compared to late planting (Table 4). Similar to season 2, planting date significantly ($p < 0.05$) affected the 1000 seed weight by the in season 3. The late planted sorghum was significantly ($p < 0.05$) greater than early planted sorghum (28.73 and 23.15 g, respectively) (Table 5). Moreover, significantly ($p < 0.05$) greater 1000 seeds weight was observed when sorghum was planted under NT compared to CT plots (29.44 and 22.44 g, respectively) (Table 5).

Discussion

The significantly higher P and K levels under NT in the second growing season could be attributed to crop residue retention. Crop residue retention improves the availability of P by reducing its adsorption onto mineral surfaces [25]. Consistent with these findings, previous studies have also reported improvements in P and K under NT with crop residue retention [2,26,27]. NT minimizes soil disturbance, preserving soil structure and promoting the activity of beneficial microbial communities that contribute to nutrient cycling and availability. Similarly, the elevated SOC observed under NT plots in season two and three could be due to the combination of crop residue retention and low soil disturbance. Plant residue retention and low soil disturbance improve soil organic carbon through decomposition process, consequently, increases SOC content [28,29]. The results of this study were consisted with the findings by Villamil et al. [29] who reported improved SOC within the 15 cm soil depth under NT with biomass residue retention compared to CT treatment on a silt loam soil. Dou et al. [30] found that, SOC was 34 – 37 % higher under NT treatment than CT treatment in grain sorghum production on a silty clay loam soil. Moreover, the increase in total N under NT in the third growing season could be attributed to the addition of crop residues, which might have increased the activity of microbes, which are responsible for nitrogen fixation [2,27,31]. The results of this study are consisted with the previous study by Malobane et al. [2] who reported that total N was 15.85 % higher under NT than CT plots in sandy clay loam soil under sweet sorghum production system. The non-significant effects of rotation on the measured soil properties suggest that other factors may have played a larger role. Moreover, the short duration of the study may have limited the potential of the treatments to have any meaningful impact. Additionally, poor crop residue retention due to extreme temperature and limited vegetative growth, particularly under crop rotation with cowpea likely masked the potential benefits of residue retention. When plants are experiencing water stress and extreme temperatures they stop growing and quickly start flowering hence switching to the reproductive stage to quickly complete their life cycle [32]. This poor biomass production may also have masked any potential effects of tillage and rotation on nutrient cycling and soil health.

The results of this study suggest that the taller sorghum plants observed in the second growing season could be attributed to the observed higher K content at early planting. The taller sorghum plants observed when Pan8816 cultivar was planted under NT system in the second growing season should be attributed to low soil disturbance and the addition of the plant residues, which might have improved P, K, and SOC. Thus, phosphorus, potassium and SOC were higher under NT plots in the second growing season, which might have played an important role to enhance the growth development of the sorghum. The plant residues retention might also improve soil water availability by reducing evaporation and runoff. Moreover, the results show that Pan8816 did well under NT whereas Macia performed better under CT in the second season, which might be attributed to the cultivar's genotype adaptation under different tillage systems. However, both cultivars performed well under both NT and CT when planted early, thus highlighting the importance of timeous planting.

The significantly higher dry matter observed with early planting in the second season could be attributed to the taller sorghum plants produced at early planting date. Plant height has a positive relationship with dry matter yield, indicating that, taller plant accumulates more dry matter [33]. The higher yield at early planting in season two could be attributed to the observed improved plant morphology. Early planting resulted in taller sorghum plant, greater dry matter yield and 1000 seeds weight compared to late planting. Plant height, dry matter and 1000 seeds weight were consistent with the results for sorghum yield in season two of this study. Generally, taller plants with a greater dry matter accumulation are better equipped for water extraction, which promotes crop growth

Table 5

The effects of planting date, tillage, cultivar and rotation on plant height, dry matter, yield and 1000 seed weight in the third growing season.

Third growing season (2021 – 2022)					
Treatment		Plant height (cm)	Dry matter (t/ha)	Yield (t/ha)	1000 seeds weight (g)
Planting date	Early	106	2.60	1.51	23.2 b
	Late	104	2.21	1.32	28.7 a
		ns	ns	ns	$p < 0.05$
Tillage	NT	103	2.31	1.29	29.4 a
	CT	107	2.50	1.54	22.4 b
		ns	ns	ns	$p < 0.05$
Cultivar	Pan8816	105	2.12	1.39	27.4
	Macia	105	2.69	1.43	24.5
		ns	ns	ns	ns
Rotation	S-C-S	106	2.21	1.45	24.0
	S-S-S	103	2.60	1.37	27.9
		ns	ns	ns	ns

Note: Different letters (a and b) – significant differences ($p < 0.05$); ns – no significant; NT – no-till; CT – conventional tillage; S-C-S – sorghum-cowpea-sorghum; S-S-S – sorghum-sorghum-sorghum; cm – centimeters; t/ha – tonnes per hectare; g – gram.

development through enhance photosynthesis, grain filling and hence higher grain yield [5]. The lower grain yield for late planting may also be attributed to the crop physiological stress, which might have been caused by the extreme temperatures towards the end of the crop growth [34]. These findings suggest that planting date can directly affect crop yield in Clau-Clau. Therefore, early planted sorghum could have received enough rainfall and time for development and growth.

Greater 1000 seeds weight observed at early planting in the second growing season could be attributed to several factors such as enhanced assimilate accumulation due to improved morphology e.g. taller plants, higher dry matter, and sorghum grain yield. Early planting allows for a longer growth duration from the emergence stage to the flowering and panicle initiation, which promotes higher nutrient assimilation [35]. This could have positively influenced the seed weight. Early planting also ensures improved resource utilisation through the establishment of stronger root systems and better access to soil moisture and nutrients. According to Hadebe et al. [5], a higher plant biomass accumulation enhances water extraction for growth and photosynthesis. This improved resource utilization ultimately contributes to larger and heavier seeds during the crucial grain filling stage. The greater 1000 seeds weight under NT plots could be attributed to the low soil disturbance and crop residue retention, which might have improved soil water availability in the third growing season. Crop residue retention improves soil temperature and water availability by decreasing soil water loss through evaporation and runoff, consequently, enhanced seed weight during grain filling stage. Soil water is one of the vital factors to influence crop growth and yield [36]. Similarly, higher seed weight was reported under NT compared to CT treatment which was attributed to the improvement of soil water under NT by reducing water evaporation [37].

Conclusion

This study provides insights into the short-term effects of CA on sorghum production in sandy soils. The results demonstrated that sorghum-based CA systems can significantly improve crop yield, SOC and total nitrogen in some sandy soils in the short-term (3 years). While CA alone does not consistently improve crop yield in the short term, the findings also highlight that its combination with optimal planting date significantly improves crop yields and soil properties, with better results being realised during seasons with higher rainfall. This study also demonstrated cultivar-specific responses of sorghum to planting date and tillage, with better performance for Pan8816 under NT and Macia under CT when planted late. Therefore, this finding provides a new perspective on maximising the benefits of CA on yield in similar environments. These observations provide valuable, location-specific guidance for farmers in the Clau-Clau region and similar environments. The lack of short-term rotation effect observed in this study suggests that for sandy soil, short-term external applications of organic fertilizers, such as manure, may be more beneficial than crop rotation. The varied effects of planting date and tillage across seasons highlights the need for site-specific management strategies. Whilst this study provides critical short-term insights, long-term studies are necessary to fully understand the effects of tillage and rotation on soil properties and sorghum yield. This long-term research will enable the development of optimised site-specific agronomic practices, ultimately enhancing agricultural planning and decision making in similar environments.

CRedit authorship contribution statement

H.Z. Mabasa: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Software, Validation, Writing – review & editing. **A.D. Nciizah:** Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Supervision, Writing – review & editing. **P. Muchaonyerwa:** Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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